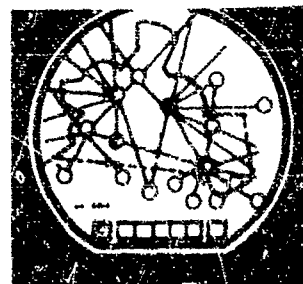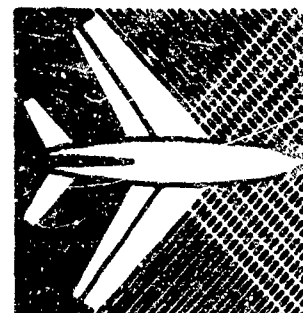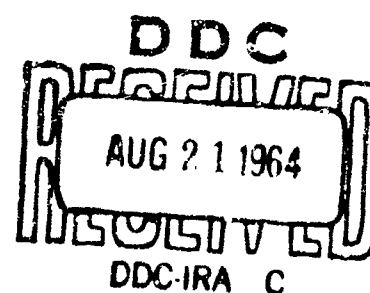Report No. RD-64-7
Project No. 113-TO-TR

SURVEY AND ANALYSIS OF LONG-DISTANCE COMMUNICATION TECHNIQUES

**Final Report
Contract No.
FAA / ARDS-487**

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NOTICES

ii

CONTENTS

FIGURES

TABLES

v

RD-64-7
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ABSTRACT

Various means of providing a reliable communication system for air traffic
control (ATC) in the North Atlantic in the 1970's have been investigated. The
study indicates that considerable improvement in the adequacy and reliability
of communication with over-ocean aircraft (during the interim period before
1970) could be obtained by the adoption of an optimized hybrid system utilizing
High Frequencies (in both ground wave and ionospheric modes); Very High Fre-
quencies (present communication band in both line-of-sight and tropospheric
scatter modes); and Low Frequencies (ground-to-air). However, the study also
indicates that the only economically and operationally feasible technique which
will fully satisfy the near-future requirements for communication to over-ocean
aircraft and which will be at all adequate for post-1970 requirements, is one
which utilizes active satellite relays. The study further indicates that, for
the communication function alone, synchronous (or 24-hour period) satellite
orbits are superior to other orbits when economics and operational procedures are
considered. This system, which provides the necessary area coverage and access time
at a reasonable cost, also protects the large capital investment of the airline
operators in VHF communications equipment.

1
INTRODUCTION

1.1. BACKGROUND

In recent years increasing air travel between Europe and the United States and Canada has
made the North Atlantic an area of concern to those organizations responsible for the safe and
efficient operation of aircraft. These organizations include international groups, such as the
International Civil Aviation Organization (ICAO) and aviation regulatory bodies within individual
countries. The Long-Distance Navigation (LODISNAV) program, sponsored by the Federal Aviation
Agency, is a concerted effort to resolve some of the problems associated with the flow of air
traffic in the North Atlantic. This report documents one part of that effort: a study of the
problem of communications between control centers and aircraft during the 1963-1975 period.

1.2. STATEMENT OF THE PROBLEM

The basic problem in the North Atlantic air-ground-air communications system lies in the
requirement for reliability and access time consistent with the needs of the air traffic con-

trol system. Although similarities exist between the requirements for communications between en route transcontinental flights and air traffic control centers, the long over-water routes and the attendant lack of surface navigation aids and communications relay points make the problem much more difficult. The situation is further complicated by the severe weather and auroral disturbances common to the North Atlantic. (The low density of flight traffic in the North Atlantic partially compensates for these disadvantages since more time is available to complete a transmission.) Minimum-time flight plans, which are used to reduce the effects of weather on flight schedules, also shift the regions of high-density traffic over wide geographic limits

from week to week. Passenger preferences result in flight schedules with periods of peak traffic followed by periods of relative inactivity. Two major pressures on the present ATC system are anticipated during the 1963-1975 period: (1) total trans-Atlantic traffic is expected to double the 1960 level, with a threefold increase in commercial flights, and (2) the supersonic transport is expected to reach full operational status.

1.3. PROGRAM ORIENTATION

Although the contract required studies of (a) aircraft-to-aircraft relays, (b) ocean-station relays (buoys), (c) satellite relays, and (d) HF data links, the FAA Project Manager and the contractor agreed that consideration of only these four methods would be unduly restrictive and that the investigation should be more generally oriented. After preliminary evaluations were completed, the field would be narrowed and the remaining methods subjected to intensive examination.

Information on an ATC model for the North Atlantic in 1970-75 was expected early in the contract period. When it became apparent that the ATC model would not be forthcoming, a portion of the contract effort was devoted to investigating ATC system problems in sufficient depth to permit formulation of realistic assumptions as a framework for the communications system analysis.

2
CONCLUSIONS AND RECOMMENDATIONS

At the outset it was anticipated that the final recommendations would specify a best satellite and a best non-satellite solution to the problem of communications for ATC over the North Atlantic in 1970-1975. Here, "best" means a judicious compromise among coverage, access time, the use of present equipment, initial and operating costs, availability of frequency assignments, the possibility of implementation by 1975 and, to a lesser extent, the possibility of being expanded to a world-wide system. However, the study has indicated that in this sense of "best" there are no really acceptable alternatives to the satellite system. The satellite system at present is only a concept; therefore, an interim system must be introduced which will permit a smooth transition from the present line-of-sight VHF (in the coastal areas) and long-range HF systems to a system built around the VHF synchronous satellite relay. The investment in the interim system

will be best used if most of the elements are usable in the 1975 system. The recommended interim system is a combination of HF skywave (for long-range coverage) and extended-range VHF (to increase reliability in the areas within its range).

The HF channels provide an immediate capability around which the interim improvements can be built. Voice capability will be retained for both HF and VHF, and thus will require a minimum of new procedures. As the more powerful ground stations and improved receiver-antenna installations required for troposcatter become available, the quality and reliability of VHF at the fringes of the line-of-sight (LOS) region will be immediately improved. At present jet altitudes, LOS is 280 miles, supersonic jets (80,000 feet) will extend this to 400 miles. Thus, benefits from the interim system will become evident even before all aircraft have the low noise receivers and increased transmitter power required for full troposcat operation.

The additional reliable range possible with fully implemented tropo operation is now in the process of critical evaluation by both the FAA and the Air Force. The communication problems arising from gaps in HF coverage due to skip-zone phenomena will be minimized. Also, the HF channel load will be reduced by providing VHF coverage for those portions of trans-Atlantic flights which require most frequent ground contact.

In the later stages of implementing the interim system, the installation of digital equipment (required for the satellite system) could provide another increment of range for the troposcat system since digital transmission makes better use of the available power.

While a number of problems must be solved before a VHF satellite communication relay can be implemented, most of these are engineering problems rather than fundamental scientific difficulties.

The postulated VHF satellite relay has the capacity for two relatively narrowband digital channels, each having enough capacity to handle the air-ground-air ATC communications load for the aircraft traffic expected in 1975. While digital data transmission would be employed when aircraft were beyond the range of land-based facilities, it is anticipated that standard VHF voice channels (troposcat or line-of-sight) would be used near the terminal ends of the transoceanic flight paths. Since digital input and output equipment will apparently be provided by the airlines for operational traffic in domestic areas (expected to be available in the early 1970's; see Section 3.1), a data rate conversion should permit use for oceanic ATC as well. With the addition of such digital input and output equipment and of new aircraft antennas to the present VHF equipment, digital data transmission can be provided through the satellite relay. The present usage of HF for long distance over-ocean communications, where the operational traffic of the airlines constitutes a large part of the total communications load, suggests that the airline operators will wish to retain this voice capability. However, the decision to retain the HF capability for operational traffic clearly must be made by the airlines industry on the basis of need and the feasibility of continuing to provide adequate ground station coverage if ATC facilities are moved to other bands.

Although the digital link provided by the VHF satellite would be suitable for highly reliable transmission of emergency messages, it is possible that pilots (with their present lack of experience and confidence in digital systems) will insist upon a voice capability for emergency situations. The presently installed VHF double sideband equipment used in conjunction with the postulated VHF satellite system would not have such a capability. By replacing the present VHF equipment with either feedback FM (FBFM) or single sideband, a voice capability would be possible, although the need for it in over-ocean air traffic control has not been demonstrated. A thorough study to delineate actual requirements (as opposed to traditional uses) is needed before investing extensively in new aircraft and ground equipment.[1]

The recommended satellite system could ultimately be extended to provide world-wide coverage of remote and oceanic areas with a single unified system compatible with domestic facilities. The elimination of the multiplicity of communications equipment now required for international airline operation would result in considerable savings to the airlines.

Satellites for ATC communications (ATSAT) over the North Atlantic by 1975 will require positive action on the part of the FAA if implementation is to be effected promptly. The concept of communicating via satellites with mobile stations introduces problems which are not being solved by research and development efforts devoted to point-to-point relay systems such as Telstar and Syncom. Because of the specialized nature of these problems, their solutions are not likely to be forthcoming unless the FAA establishes a positive program.

Specific needs requiring early consideration are enumerated below.

(1) Developing a system model for the 1975 North Atlantic ATC system. This effort is fundamental. Subsystem requirements in the areas of communication, navigation, and operating procedures cannot be formulated until the results of such a program are available.

(2) Actively supporting tropospheric scatter research and development programs to establish reliable operating ranges for the air-ground-air environment and to establish the operational characteristics which can be expected from an extended-range VHF system.

(3) Developing those digital components which are unique in the satellite relay system and supporting the development of those domestic data link components which are compatible with the satellite system.

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[1]This decision may be influenced by any potential equipment changes in the domestic ATC system. For example, while FBFM can offer significantly higher audio signal-to-noise ratios than single sideband for a given amount of transmitter power, single sideband is preferable when channel allocation space is limited. Even if one of these systems were to be used domestically at a later date, the satellite relay would not have to be modified to accept FBFM or single sideband instead of the present AM since it is a frequency translation system capable of handling any form of modulation within its bandwidth capabilities. Therefore a satellite with a 25-kc bandwidth would be able to handle AM, double or single sideband, or FBFM.

(4) Determining the optimum method of providing many aircraft with access to a single satellite relay. Alternative approaches must be compared to the roll-call methods discussed herein.

(5) Designing aircraft antennas suitable for economical retrofit to the existing air carrier fleet, as well as incorporation into new designs. Switchable arrays appear to provide the best compromise between costs and required gain.

(6) Applying existing design techniques to specific VHF satellite problems (unfurlable antennas, rugged long-life tub s and semiconductors, etc.)

(7) Monitoring existing communications and satellite programs to insure prompt utilization of developments which are directly applicable to VHF satellite problems. Among these developments are

    (a) techniques of satellite vehicle design

    (b) techniques of synchronous-satellite attitude stabilization

    (c) improved prime-power sources

    (d) increased payloads and higher probability of successful launch (resulting from the continuing NASA and military space programs)

    (e) improved modulation, coding, and detection techniques

(8) Examining the concepts of a transonic control zone and of automatic instrument interrogation suggested in Section 3.3.1. Definitions of the operating procedures and equipment requirements must be derived from the system model before the merit of these concepts can be fully evaluated.

(9) Initiating necessary negotiations to provide the four VHF and four UHF clear channels required for the ATC satellite system.

3
DESCRIPTION OF THE ENVIRONMENT: THE NORTH ATLANTIC, 1975

The air traffic control complex in the North Atlantic has developed during the formative years of trans-Atlantic commercial flight. As the aircraft changed, problems arose and were solved individually. Only in recent years has there been a significant effort to relate the problems to the entire system. The LODISNAV program initiated by the FAA is a major step toward early definition of the subsystems expected to exist in the 1970-1975 era. However, the ultimate goal must not be a set of unilaterally optimized subsystems, but rather an integrated program of system analysis.

Certain basic aspects of the system modeling problem are discussed in Section 5. However, the development of a complete ATC model with all its subtle interdependencies will require the application of the most sophisticated modeling techniques available.

3.1. SUMMARY OF ASSUMPTIONS

The design of a communication network of which not one major element is firmly defined requires assumptions. Since no systems analysis data were available at the time this study was conducted, these assumptions were unilateral. It is hoped that no great injustice has been done to the companion subsystems which must eventually be integrated into a single workable ATC complex. To the greatest possible extent, the opinions of informed sources in other specialties have been solicited and considered. In the final analysis, however, the assumptions must be viewed as a best estimate, hopefully conservative, of the future status of a system which is, and will continue to be in the next decade, subject to numerous technological and economic pressures that promise to invalidate present concepts of oceanic air traffic control.

The following statements, although not essential to the success of all the proposed systems, constitute the "ground rules" under which the investigation was conducted.

(a) In recognition of the rapid conversion to turbine-powered aircraft, it is assumed that the great majority of aircraft will fly above 20,000 feet. For communications systems in which coverage is a function of altitude, this 20,000-foot level is the minimum for which complete coverage must be provided. Alternative methods of providing emergency communications below this "floor" altitude are required, but the design conditions are very different.

(b) Digital transmission of ATC messages for the en route portions of North Atlantic flights is functionally acceptable.

(c) Digital communications for domestic routes will be implemented in the next decade. The present government plan for utilizing national airspace does not emphasize "data links." However, the airlines themselves, as evidenced by their participation in such activities as the Radio Technical Commission for Aeronautics, Special Committee 100 (RTCA SC-100), have indicated a desire to implement a data transmission capability and, in the absence of any national program, may do so on a private facility basis. There will be strong economic pressures in the next decade to make available the advantages offered by digital-information transfer.

(d) Provisions for carrying airline operational messages on the ATC communications channels is not considered mandatory. It is recognized, however, that space and equipment economy are best achieved by using the same equipment wherever possible and, in addition, that some provision must be made for operations traffic.

(e) Cost to the user airlines is a major factor in the ultimate acceptability of any proposed communication system. Not only initial outlay but also operating expenses, aircraft performance penalties, and influence on operating procedures which could affect costs are important. Therefore, proposed systems should make maximum use of present aeronautical radio equipment to protect the tremendous investment it represents.

(f) Since channel capacity requirements will be affected by the technological advances of the next decade, the impact of commercial supersonic transports and weather navigation and communications satellites must be fully considered in relation to any proposed ATC system.

6

(g) The aircraft traffic figures used are based on predictions published by the FAA. The communications message load is derived by assuming that each plane requires a given average amount of channel time while it is in the air.

Within the bounds imposed by these principal assumptions, the concept of communications and air traffic control contained in the remainder of Section 3 was evolved. In this context the propagation theory in Appendix A was evaluated and the system recommended in Section 4 was selected.

3.2. TRAFFIC

Since no system model was available, the communications channel capacity requirements were estimated by extrapolating present requirements in proportion to the anticipated increase in air traffic by 1975.

The following assumptions were used as the basis for the projections:

(a) By 1975, 900 flights a day are expected in the North Atlantic region during the peak traffic seasons [1].

(b) The peaks in traffic over a 24-hour period result in uneven demands on ATC communications facilities. To approximate the peak message loads, assume that all flights during a 24-hour period are concentrated in a 10-hour period with traffic density constant [2]. Thus the assumed traffic is

$$\text{Assumed maximum flights/hour} = \frac{\text{total flights in 24 hours}}{10}$$

(c) From the distribution of aircraft types (Table I) a mean flight time of 3.1 hours is calculated for the northern Europe-to-United States flight path, which represents the major North Atlantic routes.

TABLE I. EXPECTED DISTRIBUTION OF NORTH ATLANTIC
AIR TRAFFIC FOR 1975

Aircraft Type	Distribution of Traffic (%)	Approximate North Atlantic Flight Time (hours)
Turboprop	2	8.5
Subsonic Turbojet	26	5.2
Supersonic	72	2.2

(d) At present, the major part of ATC traffic consists of air-to-ground messages. The communications requirements are based on the assumption that this will continue to be true in 1975. Ground-to-air ATC and weather messages are discussed after the air-to-ground requirements are derived.

7

(e) On the average, each aircraft makes four position reports an hour — a figure based on a somewhat arbitrary averaging of typical reporting frequencies presented in the Request for Proposal for this contract (i.e., two to three reports per hour in mid-ocean and as many as six per hour in coastal zones). It is considered quite conservative for systems similar to the present ATC system, but is sensitive to any change to more "tactical" control doctrines.

(f) The information required for position reporting (and, optionally, weather data) could be transmitted in a 7-bit alpha-numeric code similar to that recommended by RTCA Special Committee 100 and the ASA. Standardized abbreviations and a specific format for routine reports could reduce the number of symbols in the messages. Since the coding of the alpha-numerics does not depend on such restrictions, it would also be possible to send normal clear text when necessary.

Appendix D illustrates the contents and bit requirements of a typical message. A typical position report could be transmitted with approximately 50 characters of 350 bits. An additional 350 bits (air-to-ground) would permit a moderately detailed aircraft weather report.

From assumptions a, b, and c, it can be determined that 278 flights are in the air simultaneously. In conjunction with assumptions e and f, this result leads to an approximation of 110 bits/sec (about 157 wpm) for the position report data. If weather data is included, a total of approximately 220 bits/sec (air-to-ground) are required. If a 500 bits/sec channel (i.e., the recommended satellite data rate) is used, these messages require respectively 13.2 and 26.4 minutes of channel time each hour.

Note that this channel-capacity requirement does not include ground-to-air traffic, company-operation traffic, or any provision for non-standard messages. However, it does represent the bulk of ATC traffic. Also note that channel time estimates are based on digital transmission; therefore it will be necessary to convert to hard copy, visual display, or voice. At least one working prototype of a digital-to-voice converter has been demonstrated [3].

Ground-to-air weather channel requirements can be approximated by noting that LF radioteletype weather broadcasts are transmitted from Scotland 24 hours a day at a rate of 45 bits/sec; they provide reports of actual and predicted weather (in clear text) for all important airports on the European side of the Atlantic. A similar coverage of the American side would be required. If the total bit requirement is scaled for a 500 bits/sec channel, then

$$2 \times \frac{45}{500} \times 60 = 10.8 \text{ minutes of ground-to-air weather}$$
$$\text{transmission required each hour}$$

These values are based on a communication system with negligible propagation times. The effects of the approximate 0.3-second delay involved in ground-to-24-hour satellite-to-aircraft relay have been evaluated by using the traffic and message assumed above. A single 500 bits/sec simplex data channel was assumed to operate in one of two modes:

(1) A roll-call system which assigns a specific time for each aircraft to report. This system requires a precise time reference for the aircraft.

(2) A roll-call system which requires that each aircraft be addressed by the ground station and directed to file its position report.

In each case, if weather data is transmitted, it is assumed to have been appended to the position report. The first mode transmission time is 13.3 minutes for position reports only, and 26.5 minutes if air-ground weather is included. This difference, caused by differences in propagation time for aircraft at opposite extremes of the coverage area, is negligible.

The second mode, on the other hand, increases the position reporting time to 24.0 minutes each hour (24.0 + 13.2 = 37.2 minutes, if weather data is included). The additional time required results from transmission of the paging message and the propagation time for the synchronous satellite channel.

The time remaining for unscheduled transmissions and ground-to-air ATC messages appears adequate (at worst, 60.0 - [37.2 + 10.8] = 12 minutes per hour).

Without the benefit of a valid system model, speculation on the effects of modifying the assumed basis for data rate predictions is necessarily qualitative. The following factors could appreciably change channel capacity requirements:

(a) Conversion to a tactical control doctrine would increase data rate requirements.

(b) A satellite-borne position determination system would shift much of the channel requirement from the aircraft-to-ground channels. Ground-to-aircraft links would be more heavily loaded, and, in addition, communications between the position-determining satellites and ground stations would be required.

(c) Modification of reporting procedures within the framework of the present ATC philosophy might reduce channel usage by a factor of two or three.

Resolution of the actual data rates must await development of an adequate system model. The assumptions above are quite conservative. Also, there is a surplus time remaining after essential transmission which may be used as necessary.

If, after the ATSAT system had been placed in orbit, a need for even greater capacity arose, the second or "spare" ATSAT channel could be pressed into service. It should be noted, however, that the reason for recommending this channel was to increase reliability and avoid catastrophic failure. Without this protection, the number of satellites in orbit would have to be increased to maintain the desired backup. As noted in the cost section, the cost of an additional satellite would be high and additional clear channel frequencies would be required.

Since it seems unlikely that additional capacity would be required for a number of years after inception of ATSAT operation, the most desirable method of increasing capacity would be a second-generation system with increased power and higher data rates. The large boosters now being developed should provide adequate launch capability for heavier satellites and should have a reliability commensurate with their planned use in the manned space flight programs (see Appendix B.1.5).

9

3.3. PROPOSED ATC INNOVATIONS

In the course of this investigation it became apparent that two capabilities, not available in the present ATC system, would prove useful regardless of the communication system eventually adopted. A brief discussion of each is presented.

3.3.1. TRANSONIC CONTROL REGION. Operating proposed supersonic transports (SST) economically depends on the freedom to select optimum conditions for the transition from subsonic to supersonic flight. During this critical phase, air traffic will necessarily require close surveillance by the traffic controller. The supersonic transport must, by one means or another, penetrate dense traffic of domestic, coastal and over-ocean aircraft of many types, including other supersonic transports, in an air traffic control region extending 300 to 400 miles from the port-of-entry. It, therefore, seems essential that fast, reliable, and flexible communications to the supersonic transport be available. Fortunately, the probable ascent and descent profiles of the proposed SST are quite similar to radio line-of-sight profiles, so it is reasonable to postulate a line-of-sight communication capability (as well as radar observation) in much of the transition range. This is discussed further in following paragraphs.

Since economical operation in the transonic portion of the flight depends on meteorological conditions, very detailed and up-to-date weather information will be required. The extent to which communications requirements can be reduced by preplanning the acceleration to supersonic flight will depend on the success in providing adequate weather data.

The present terminal control center is responsible for an aircraft from take-off until the transition to en route flight conditions is complete. The advent of supersonic aircraft will extend this transition region because of the greater distances traveled during acceleration to cruising Mach numbers.

If projected supersonic transports are free from anti-noise restrictions, as they would be if acceleration took place over the ocean, a zone extending 300 to 400 miles from the terminal would provide adequate acceleration space for the aircraft [4]. Typical fuel consumption rates for a projected supersonic transport during acceleration (approximately 200,000 lb/hr) emphasize the magnitude of the problems encountered in transition to supersonic speeds. If the transport is required to accelerate during non-optimum meteorological conditions, an additional 10% to 20% of the total fuel required for acceleration may be consumed. At the fuel rate just noted, this is entirely unacceptable since the capacity for carrying fuel reserves will be severely limited.

By providing an efficient and rapid approach to the terminal, the transonic control region would be of equal value for descending aircraft. The communications ranges required during ascent and descent are roughly equal, depending on the g forces which are acceptable to the passengers. Deceleration may be accomplished in 95 to 420 miles with corresponding g loads of 0.27 to 0.05 g [4]. The 0.27-g figure is normal military procedure, but requires considerable familiarization before passenger anxiety can be eliminated.

Since range, reliability, and channel capacity requirements in the transonic zone are quite different from en route communications, separate implementation for the transonic region

appears feasible. The altitudes at which deceleration begins are expected to be 65.000 to 70,000 feet; thus both ascending and descending aircraft would have the advantage of very high altitudes when communication ranges are greatest.

During typical ascent and descent profiles the SST would be within line of sight of the control center and would benefit from improved transmitters and receivers which would extend radio range to the increased line of sight resulting from high altitudes. For flight profiles which fall below line of sight and for extended ranges, two propagation modes may be considered: (1) tropospheric scatter and (2) groundwave HF. The required ranges are within the theoretical capabilities of both modes. Implementation in the 1970-1975 period, by which time the SST may be expected to constitute a large part of the total traffic, is expected to realize those capabilities.

3.3.2. INTERROGATION OF AIRCRAFT SENSORS. To perform his functions properly, the air traffic controller must have access to aircraft navigation, altimetry, and velocity instruments.[2] With the exception of flight-following operations, the exact information required and the rate at which it must be received by the controller depend upon the nature of the departure from the flight plan or the seriousness of a potential conflict.

It is recommended that provisions be made for the selective digital interrogation of appropriate flight instruments. It may be possibl to use portions of the present VOISPOND technique (used by some airlines for flight following) to implement such interrogation. There are several potential advantages of an interrogation capability:

(a) The pilot is relieved of the burden of providing information.
(b) Because digital data are used, the transmission time, as well as the accuracy, is expected to improve (i.e., human reaction time and errors are eliminated). Further, digital transmission with its minimum of 14.5-db power advantage over analog transmission will also improve the accuracy of the received messages.
(c) Since the information can be transmitted in computer format and certain routine computations performed before the information is presented to the air traffic controller, more effective use can be made of his time.

3.4. FREQUENCY ALLOCATIONS

Throughout this report primary guidance in frequency selection has been obtained from Principles and Practices of Frequency Management, General, issued by the Federal Aviation Agency, Frequency Management Staff Division [5]. Personal contacts with the personnel of that Division and of the Communications Section of the Department of State provided additional insight.

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[2] At present, all information about an aircraft's flight status and position are obtained from the aircraft itself. If proposed systems for determining aircraft position externally (from satellites, for example) are implemented, the interrogation program could be easily modified to request some data from the aircraft and some from the satellite (or its processing center).

Wherever existing aeronautical bands were considered technically suitable, they have been specifically recommended. Two factors dictated this approach:

(a) Frequency allocations are immediately available; thus implementation delays occasioned by lengthy negotiations for new frequencies are avoided.

(b) The substantial investment represented by the equipment presently operating in these bands is protected.

The propagation modes discussed provide acceptable performance over a much broader range of frequencies than the recommended band encompasses.[3] If, for any reason, operation in an adjacent band should be considered desirable, this would, in general, be acceptable.

4
SYSTEM SELECTION

4.1. SYSTEMS CONSIDERED

The systems selected for evaluation were thought to be useful either in single mode or in combinations. The pertinent propagation theory is presented in Appendix A.

Specific modes considered were:

(a) Skywave
(b) Groundwave
(c) Tropospheric scatter
(d) Ionospheric scatter
(e) Meteor scatter
(f) Line of sight
(g) Satellite relay

With the exception of satellite relays, no single system seemed capable of providing the required quality of service and coverage for a reasonable expenditure of resources (time, money, spectrum usage). However, several modes, if combined with the existing HF system, have possible applications in the pre-satellite interim system. Table II compares four such modes.

4.1.1. SKYWAVE. The backbone of the present ATC communication system for aircraft flying the North Atlantic is HF skywave propagation. In spite of severe limitations, it will retain this role until ATC communication satellites become available. Even then, until the power limi-

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[3]One exception is the HF modes which are limited by antenna considerations at the lower frequencies and by poorer performance at the high end of the band.

TABLE II. COMPARISON OF PROPAGATION MODES

MODE	CARRIER FREQUENCY	AIR-GROUND-AIR RANGE[a]	BANDWIDTH OR DATA RATE	LINK RELIABILITY	IS THERE AN EXIST-ING AERONAUTICAL ALLOCATION AVAIL-ABLE?	CAN EXIST-ING GROUND AND AIRCRAFT EQUIP-MENT BE USED?	COMPATIBLE WITH: DOMESTIC SYSTEM/ VHF SATELLITE?	RELATIVE COST (1 = Lowest)
HF Groundwave	3-18 Mc	300-500 miles	Voice	Good[b]	Yes	No[c]/yes[d]	No/no	1
Tropospheric Scatter	50 Mc - 10 Gc. Aeronautical VHF band (118-136 Mc) recommended	Reliable ranges of 300 to 400 miles may be achievable but reliable estimates are not yet available	Voice	Link reliability is a function of range and cannot be established independently	Yes	No[c]/yes[d]	If VHF is used: yes/yes	2
Line-of-Sight Relay (Aircraft-to-Aircraft)	Any. Aeronautical VHF band (118-136 Mc) recommended	Line-of-sight be-tween relaying A/C for each hop (to the limits set by power sensitivity and di-rectivity capability of the airborne equipment). Total range limited by continuity of re-lay net	Voice capability (controlled by use of existing RF equipment) but digital trans-mission more practical for auto-relay	Unknown—but potential long delays and out-ages result if relay net is broken. Good when net is present	Yes—if present frequency alloca-tions are utilized	RF ground and A/C usable—need auto-relay equipment	If VHF is used: yes/yes	3
Ionospheric Scatter	30-60 Mc	≈ 1000 miles	60 wpm teletype	Moderate error rates (10-3)— good availability	No	Possible modifi-cation of exist-ing HF or VHF A/C equipment	No/no	4

[a] Minimum range which will provide substantially complete coverage of the North Atlantic (between 30° and 70° North) from land-based stations is 900 miles.

[b] Groundwave reception is usually good during periods when HF skywave propagation is "blacked out" because of reduced atmospheric noise propagation from distant noise centers.

[c] New ground antenna installations required. High-power ground transmitters (kilowatt region) required for troposcat and desirable for groundwave.

[d] Some modification for improved performance is desirable, but A/C equipment will function as presently installed.

tations in the satellite are overcome, HF will remain in use for transmitting the routine informa-
tion — which cannot be accommodated by the limited satellite channels — to aircraft flying the
North Atlantic route.

The present HF skywave propagation system is unsuitable for ATC communications over the
North Atlantic in 1970-1975 because

(a) The reliability of the propagation mode is inadequate for anticipated ATC re-
quirements.

(b) The available HF assignments are inadequate for anticipated peak loads if
voice communication is retained.

(c) Even when voice communication is technically possible, atmospheric noise and
multipath propagation often make the quality very poor.

The second and third factors can be minimized by transmitting all routine ATC messages
over a digital link instead of by voice. This would also improve the reliability of communi-
cations. However, outages lasting three hours or longer occur even between fixed stations using
high power transmitters, highly directional antennas, and the most modern modulation and coding
techniques. Such outages would be intolerable in an ATC system in 1970-1975. During HF sky-
wave blackout, communications can be maintained only by using frequencies outside the HF band
or by using other modes of propagation.

In the auroral zone the long-term reliability of an HF skywave link similar to the existing
ATC system (i.e., four or five frequencies available for selection at any given time) has been
estimated at 60 to 70% [6]. In an attempt to improve HF skywave aircraft communications in the
auroral zone, the Canadian Defence Research Telecommunications Establishment conducted trials of
frequency-sounding equipment [7]. Several conclusions are pertinent here:

(a) A well-spaced set of operating frequencies across the entire available band is
required if maximum benefit is to be obtained from sounding techniques.

(b) Propagation conditions change rapidly during ionospheric disturbances; therefore,
the channel-sounding equipment must be capable of rapid cycling through the
available frequencies.

(c) During disturbed conditions, propagation via modes other than the normal F-layer
mode (e.g., sporadic E) is common. The frequencies required are quite different
from those normally used. Sounding appears to be the only practical way of
taking advantage of these anomolous conditions.

Loss of contact was greatly reduced by the use of sounding information but there were unac-
ceptably long periods during which communication was not possible.

In another investigation of auroral zone HF skywave propagation, the performance of a hypo-
thetical network of ground stations was predicted by using data from the three-day ionospheric
disturbance of September 1957 [8]. A triangular grid of stations spaced 2800-km apart in the
region from 40° North 90° North between Greenland and Alaska, was postulated. Frequency switch-
ing in the 3 to 30-Mc band was used. Also, whenever direct contact was not possible between

14

stations, link switching was used to relay traffic over paths which were operating. On this theoretical basis, a reliability above 90% was achieved. However, in spite of the frequency and link switching employed, there were still six-hour periods of complete blackout (approximately the time required for a jet Atlantic crossing) on each link studied. Thus, while the reliability of HF skywave communications in the auroral zone can be improved by optimum choice of paths and frequencies, it must be remembered that without such flexibility the reliability is very poor indeed. The present HF system, while not designed to choose the best path and best frequency rapidly and automatically, does have several widely spaced ground stations and weather ships monitoring the aircraft frequencies. No doubt this network could be improved and made more efficient by automatically testing and selecting the optimum combination of links at any given time [9], but, as shown above, the potential for improved operational reliability has been at least partially exploited in the existing system.

The multipath properties and the high atmospheric noise level are inherent in this mode of propagation. For data transmission over an HF link, a high quality service can be provided by using sophisticated coding techniques and a data rate which is low in comparison with the available channel bandwidth [10]. For improved voice communication over HF links, comparable techniques have not been developed and their widespread use in the future is unlikely since the bandwidth for applying these noise and multipath suppression techniques to voice communications is not available in the crowded HF region.

The limited capacity of the present HF system for ATC is partially attributable to the use of voice communications for transmitting messages which can be transmitted more efficiently by other forms of modulation or coding. If air traffic increases as predicted, the present voice HF system will become overloaded. Therefore, some changes in present procedures will have to be made. From a technical point of view it would be desirable to convert concurrently all routine voice ATC communications to a data link system. This would not only result in more reliable ATC communication in the HF region, but the digital input-output equipment would be available for the proposed VHF satellite data link. The use of an HF channel by both an ATC data link and a voice communications system has undesirable features; but it might be a necessary compromise if the HF communication load should become too heavy. As the traffic load increases, it is expected that an interim system employing VHF tropospheric scatter would be phased in to reduce the load on HF channels.

4.1.2. GROUNDWAVE. Signals propagated by groundwave can provide reliable service over ranges adequate for complete coverage of the North Atlantic if frequencies in the LF region are used. Unfortunately, air-to-ground transmission is not possible in this frequency range with antennas suitable for airline use. Air-ground-air operation is feasible in the HF band; however, depending on frequency, ranges are limited to 300-500 miles.

Groundwave LF is in use at present for ground-to-air service and will probably continue to be useful in an interim system for meteorological information. However, the limitations of one-way transmission preclude it as a primary means of ATC communication. When the satellite system becomes operational, it can assume the present functions of LF.

In the HF band the groundwave service would be quite similar in range to that available with troposcat. In general, it would be more subject to atmospheric noise interference, but it would also utilize existing aircraft equipment and would require only modest changes in ground stations — primarily, a suitably polarized antenna located near the water's edge. Thus, the groundwave mode would fill the skip-zone gaps in HF skywave propagation and, since groundwaves perform well under conditions which black out HF skywaves, it would provide more usable channels in the aeronautical HF band.

Although the development of equipment for HF use has reached a high stage, it is probable that applying accumulated knowledge to the specific problem of optimizing equipment parameters for a groundwave ATC system would result in worthwhile improvements, such as improved antennas for both ground and aircraft, greater power output from aircraft transmitters, and noise reduction in receivers to permit taking advantage of the very low noise conditions during solar disturbances. However, in view of the recommendation herein and the general trend of aircraft equipment to higher frequencies, the expense of such a development program would be more difficult to justify than that of a similar program for VHF. Also, the available HF allocations — even with improved utilization made possible by adding a groundwave capability — would not provide enough voice channels for the increased traffic conditions in the 1970's. Digital transmission, if adopted, would ease the channel overload problem.

In summary, HF groundwave would be the most desirable alternative to VHF troposcat in an interim system which employed HF skywave to provide the required long-range coverage.

4.1.3. TROPOSPHERIC SCATTER. Although the tropospheric scatter mode is applicable to a wide range of frequencies, the same economic advantages apply to the use of VHF for tropospheric scatter as apply to the use of VHF for satellite systems, i.e., the investment in presently installed VHF aircraft equipment is large and cannot be ignored. In addition, the frequency allocation problem is minimized since the existing VHF aeronautical band is in limited use over the Atlantic; therefore, a usable spectrum is available without a major change in allocation.

Although the characteristics of tropospheric scatter are reasonably well known, much of the knowledge has been obtained with point-to-point ground systems. Direct experience in aircraft·has been limited to experimental operations conducted by Pan American World Airways (PAA) over both the Atlantic and the Pacific [11, 12]. Recently two programs, one FAA and one Air Force (C-141 program), have conducted initial trials of experimental voice systems operating in the aeronautical VHF and UHF bands [13, 14]. The results should eventually define with some precision the ranges and reliability obtainable in the North Atlantic with state-of-the-art tropo systems. The achievable reliability for air-ground-air links must still be established through extensive test programs. The very long ranges associated with ducting phenomena must be separated from the true tropospheric mode before reliable tropo ranges can be established.

The primary limitation of troposcat is short range. However, installations at principal control centers (New York, Gander, and Shannon-Prestwick) would provide more reliable and higher quality communications for routes over the North Atlantic with high traffic density. The coverage would be in those critical areas where flight paths begin to converge on destinations. Ex-

16

tending the system by adding stations in Greenland, Iceland, and the Azores would further close the gaps. These stations would be best used by connecting them with land lines to the major control centers. Facilities such as the new ICAO cable could be used to advantage for this purpose.

If the concepts of an extended control zone for supersonic transports, a VHF troposcat interim system, and a VHF satellite relay are accepted, it is possible to consider a unified program of improving VHF equipment. Such a program could provide equipment compatible with domestic line-of-sight, troposcat, and data-link satellites. Continued use of VHF equipment would be assured and the airlines' investments would not be wasted on a stop-gap solution.

As noted in the discussion of the satellite relay system (Appendix B) it will be difficult to provide voice links via early satellites, and, therefore, narrowband data transmission will be employed. This could be turned to advantage in an interim VHF tropo system if the modifications necessary for narrowband data were phased-in before the satellite became available. Noise power would be reduced by narrowing the 3-kc signal bandwidth required for voice to a nominal 500 bits/sec; that is, one bit per cycle at baseband (7.8-db advantage). Also, a lower signal-to-noise ratio would be acceptable for digital transmission. The net improvements in range would depend on the allowances necessary to combat the deep fades typically encountered in troposcat (see Section A.1.3.1).

The ground installations for troposcat would require new equipment, including large antennas and transmitters in the kilowatt region. However, as in the case of aircraft equipment, use would be assured for an extended period. Though troposcat installations would be considerably more expensive than present VHF installations, there is no reason to expect unreasonably high costs since all parts of the system represent the present state of the art and require no major development effort.

4.1.4. IONOSPHERIC SCATTER. The Air Force Cambridge Research Laboratories have demonstrated the feasibility of reliable air-ground-air ionospheric scatter at 1000-mile ranges [15]. Teletype at 60 wpm and moderate error rates of approximately 10^{-3} appear to be practical values. As noted in Section 3.2, the channel capacity for essential ATC communications is relatively low, and provisions for relatively few 60-wpm channels should meet the requirements.

The disadvantages of the mode are the high transmitter power required (5-10 kw in the aircraft) and the frequency-management and economic problems which arise from the requirements for operation in the 30- to 70-Mc band. The time required to obtain allocations in an already crowded portion of the spectrum (much of which is occupied by the European, Region 1, broadcast band) is expected to be incompatible with implementation as an interim system.

Similarly, the re-equiping investment would be considerable since new aircraft receivers and transmitters would be required. Even if converting present HF or VHF aircraft equipment were feasible, an additional two orders of magnitude in transmitter power would be required. Also, new aircraft antenna installations would be necessary. New ground station installation would require approximately 50-kw transmitters and multiple diversity antenna systems.

17

In spite of these drawbacks, the reliability of the propagation mode and the long ranges achievable are sufficiently desirable in a hybrid system to justify the consideration of ionospheric scatter as a third alternative for an interim pre-satellite system.

4.1.5. METEOR SCATTER. The feasibility of transmitting data by means of meteor scatter has been adequately demonstrated. However, two characteristics of this mode are incompatible with the requirements for ATC communications for the North Atlantic.

First, successful transmission requires relatively precise alignment of the antennas. This introduces difficulties at each end of the path. Since an aircraft is a rapidly moving platform, with only moderate stability about its three axes, maintaining the desired orientation for its antenna would require complex equipment. Also, providing the necessary gain and directivity at 30 to 70 Mc would be difficult in a steerable aircraft antenna. At the other end of the path, the ground station would have to provide enough directive beams to cover the entire area it services.

Second, the burst transmission required would make it very difficult to provide service to more than one mobile station. The usual system of continuous monitoring of a reference signal by both stations would be impractical with a single ground station servicing many aircraft. Unpredictable delays between transmissions prevent use of a roll call controlled by a "master clock" to eliminate "party line" congestion, and the delays involved in a ground-controlled roll call would be prohibitive.

The requirement for speed translation devices and message storage would also impose an additional equipment burden on the aircraft.

4.1.6. LINE OF SIGHT. Two methods of implementing a terrestrial relay network were considered: (1) ocean relay stations and (2) aircraft-to-aircraft relay.[4]

The use of ocean stations to provide complete line-of-sight coverage to aircraft at the minimum altitude of 20,000 feet assumed for 1970 is considered economically impractical and technically unattractive (even more so at the present 6000-foot minimum controlled altitude). Further, the problems associated with ocean stations cast serious doubt on their utility for systems requiring fewer relays than complete line-of-sight coverage, or complete coverage at altitudes higher than the 20,000-foot minimum.

As indicated in Appendix C, there are serious switching problems associated with the relaying of messages in a system using ocean station buoys. In addition, there are the problems of se-

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[4] Relays by special aircraft maintained on station in the fashion of the Airborne Early-Warning Network were rejected because of poor on-station reliability and high costs. There have been occasional stirs of interest in the near-ideal qualifications of rigid airships (dirigibles) as relay stations. Modern designs, especially when coupled with nuclear power plants, should be capable of overcoming the traditional difficulties. Even though costs would probably be greater than those of a synchronous satellite relay, the communications capacity could far exceed that of a satellite. Serious interest in such an approach could only be justified if a military program were to be instituted which would share development and base facility costs.

18

curing buoys in deep water, stabilizing antennas, and maintaining equipment under extreme environmental conditions for extended periods of time. The majority of buoys would have to be moored in deep water (over 1000 fathoms), which would be difficult. Since this question was studied in detail by the Navigation and Guidance Laboratory of the University of Michigan, under a contract (ARDS-499) with the Federal Aviation Agency, it will not be discussed in detail here [16].

Reference 16 concludes that manned trawler-type ships would probably provide the most economical means of providing a technically satisfactory mount for a VORTAC station at sea.[5] The functions of a relay station are similar enough to those required of a VORTAC station to permit conclusions about VORTAC to be applied to a relay station. First costs for two trawlers (required to man one station) were estimated at $500,000; operating costs, mostly salaries, at $312,000 per year.

Figure 1 illustrates the number of ocean relay stations required to provide complete line-of-sight coverage (for aircraft flying at 6000 to 60,000 feet) of the North Atlantic between latitudes 30 N and 70 N. The pattern of overlap is shown in Figure 2. Note that failure of a single relay will result in a gap in coverage.

A "floor altitude" of 20,000 feet, considered acceptable for 1970, requires 54 relays. At the costs for one station listed above, 54 relays would cost $27 million to install and $16.8 million per year to operate.

One of the most critical drawbacks to the entire system is the requirement for enough frequencies to return the aircraft-to-relay messages to a shore station. The best methods for relaying to shore appear to be groundwave or extended-range VHF. Since these two modes do not permit direct relay to land for the majority of the ships, the complexity of the ship-to-shore network contributes substantially to the maintenance and reliability problem. (Another problem concerns the responsibility for maintaining an extensive relay system. Since the present ocean-station vessels are provided under international agreement by countries bordering the North Atlantic, a similar arrangement for maintenance of the relay vessels would presumably be negotiated.)

The costs and technical problems are great enough to eliminate ocean-borne relays as a practical approach to North Atlantic ATC communications.

Aircraft-to-aircraft (between en route aircraft) relay is also unsatisfactory as a primary air-ground-air communications link. The essentials of this system, described in one form by Barnes and Graham [17], are

(1) A ground-control link of high reliability and full North Atlantic coverage (specifically LF RTTY)

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[5]That is, if Coast Guard ships were not used. In the case of a relay network, the number of stations required would prohibit Coast Guard implementation.

19
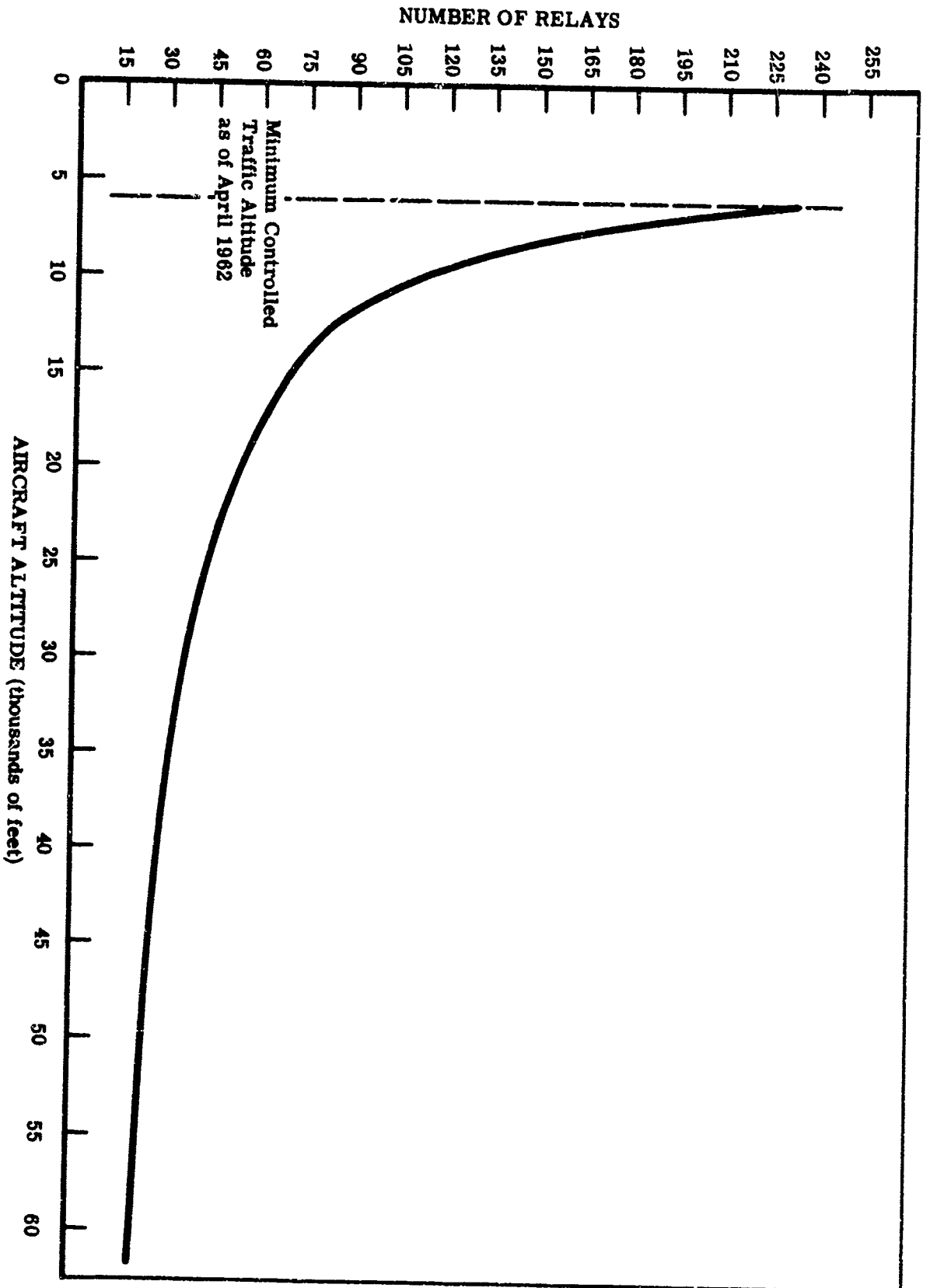
**FIGURE 1. NUMBER OF OCEAN RELAYS REQUIRED TO PROVIDE COMPLETE
AIR-TO-SURFACE LINE-OF-SIGHT COVERAGE OF THE NORTH ATLANTIC
BETWEEN 30°N AND 70°N**

NUMBER OF RELAYS

AIRCRAFT ALTITUDE (thousands of feet)

Minimum Controlled
Traffic Altitude
as of April 1962
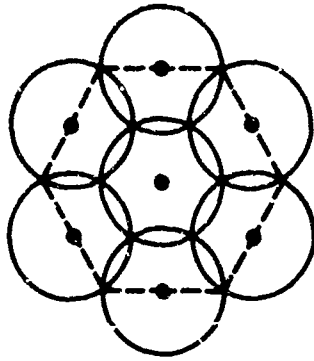
FIGURE 2. RELAY OVERLAP PATTERN

(2) An aircraft capability for receiving, storing, and retransmitting, on command, relayed messages (envisioned as a VHF line-of-sight link)

(3) The use of specific aircraft directed (by means of the LF link) to relay the message along the chain back to the ground station.

In addition to Barnes' basic scheme, several factors have been added to make the method a more effective primary system.

(1) The ground stations on either side of the Atlantic would have a direct high-speed communications capability (possibly via leased phone or data-link facilities provided by commercial communications satellites) so that an aircraft could relay a message either forward or backward to a shore station.

(2) An instrument interrogation system (Section 3.3) would be provided so that the aircraft would have the fundamentals of a digital system regardless of the communication medium.

This system is unsatisfactory for the following reasons. First, the reliability of the entire system depends upon a line-of-sight net connecting all aircraft and, at least, one ground station. Consequently, an emergency return to land by a disabled aircraft, a cancelled flight, or a radio malfunction can eliminate all communications between a large body of traffic (presumably, closely spaced in the high-traffic, 1975 era) and the traffic controller.

Second, although the paper by Barnes and Graham argues that, when traffic density is too low to permit air-to-air relay, and the need for ATC communication is minimized, it apparently does not consider that the gaps (i.e., the regions of sparse traffic) may appear at both shore-lines so that a dense mass of traffic in mid ocean becomes stranded without ATC. Furthermore, Barnes assumes that the ground station will continue to request reports from each aircraft, even though no reply is received, and that, in the process of relaying messages, each aircraft will become aware of the positions of other aircraft nearby. However, it seems unlikely that on short notice individual pilots will be able to implement an effective, cooperative ATC system capable of replacing the ground-based controller, who has the entire traffic picture at his disposal.

21

Third, the system fails to provide assured communications in emergency situations, a difficulty that might partly be overcome by carrying a rocket-launched emergency transmitter to broadcast a Mayday message.

Finally, each aircraft would require automatic message relaying equipment and a message storage capacity that far exceeded the requirements of a basic instrument interrogation system. Installing these would be costly.

Although the concept of using air-to-air relay as a primary system has been discarded, the capability for air-to-air relay should be retained in any proposed communications system. That is, nothing in a new system should prevent informal aircraft-to-aircraft communication.

4.1.7. SATELLITE RELAYS. A detailed discussion of satellite relays, the recommended ATC communications system, is given in Section 4.2 and Appendix B; however, one point regarding the use of multiple satellites in random low-to-medium altitude orbits requires emphasis here. In Appendix B this type of satellite system is discarded primarily because of cost. However, even if the cost could be made comparable to that of the recommended synchronous satellite system, serious technical difficulties would be encountered in implementing such a system to provide area (as opposed to point-to-point) coverage for a large number of mobile stations. (Appendix C discusses basic problems of routing which are especially applicable to this case.)

Specifically, consider the problem of determining which satellite will be used to relay an air-to-ground message. If broad-beam aircraft antennas are used, then more than one satellite may receive the message. Thus selective call of individual satellites or different operating frequencies are required for each satellite. (A minimum of 40 to 50 satellites would be required to provide reasonable probability of uninterrupted service.) Determining which satellite to select at a given time and geographic location is a relatively complex problem. Figure 3 indicates that this problem must be solved a number of times during each Atlantic crossing, even if SST flight times and medium-altitude orbits are assumed. Probably the best method of providing the necessary information is computation by ground-station computers and relay to the aircraft.

Similarly, the access of multiple aircraft to a single satellite requires orderly processing of simultaneous messages (e.g., busy signals or a roll call approach).

The complexity of equipment and procedures and the amount of data processing required to make a multiple-satellite system function efficiently are serious drawbacks when application to ATC communication is considered.

4.2. DESCRIPTION OF THE RECOMMENDED SYSTEM

The North Atlantic ATC communications system recommended for 1975 is a synchronous, equatorial satellite relay operating in the aeronautical VHF band. An integral part of the recommendation is the requirement for an interim system which will serve two functions: (1) supplement the existing HF skywave communications until the satellite system can be implemented, (2) serve as a transition system to facilitate the changeover to satellite communications. The satellite system itself must be understood before these two facets of the interim system can be considered.
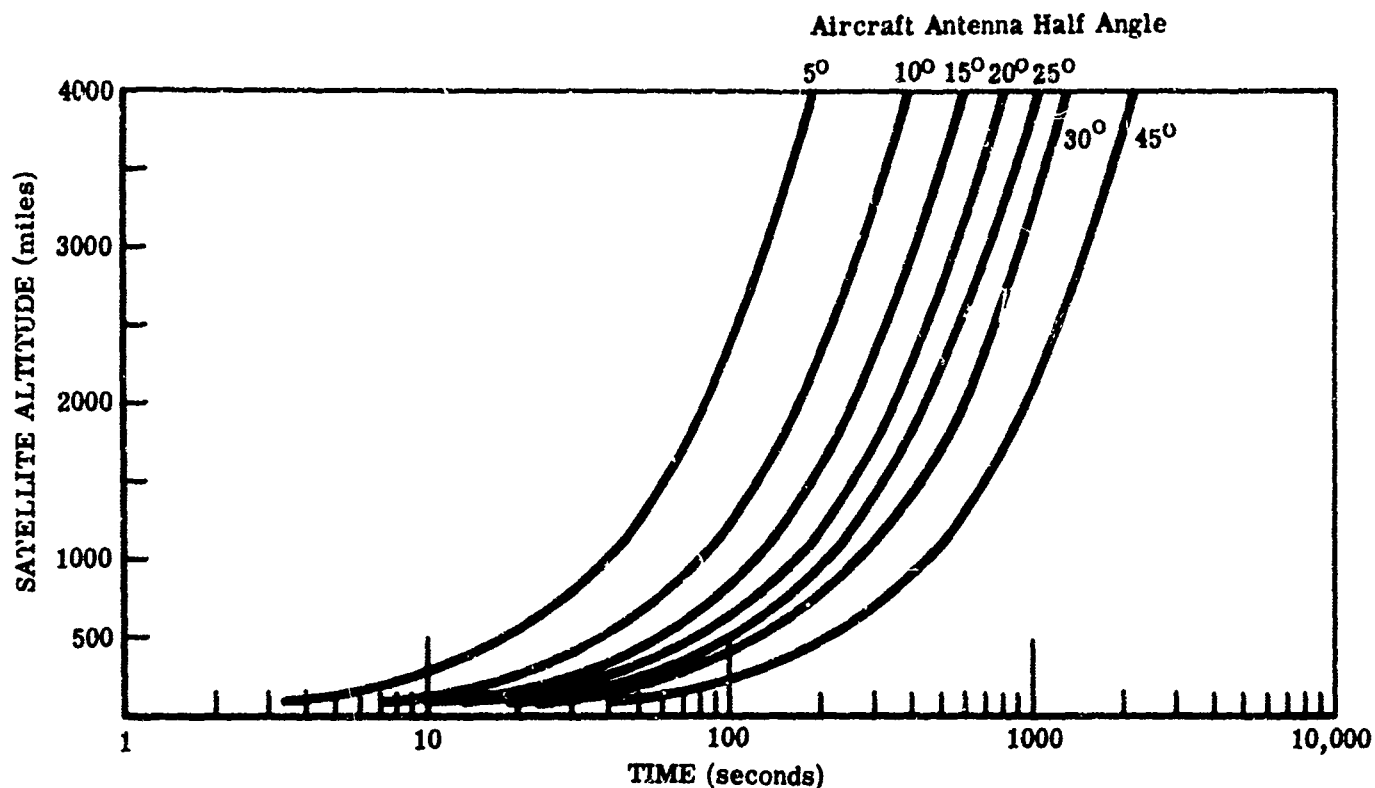
FIGURE 3. SATELLITE TIME IN ANTENNA BEAM. Fixed upward-looking
antennas.

4.2.1. **SATELLITE SYSTEM.** An ATC satellite communication relay (ATSAT) to serve all North
Atlantic ATC requirements (with digital channels) could be implemented in the 1970-1975 period
by using the VHF aircraft radio equipment now installed.

Each of the two ATSAT digital channels provided would have enough data capacity to handle
the air-ground-air ATC traffic expected in 1975. With current aircraft VHF equipment, only
digital-data transmission is possible via the satellite; however, voice will probably be used
when the aircraft are close enough for contact with land stations (VHF troposcat or line of sight).
An emergency voice capability via a satellite could be provided by replacing the present AM
double-sideband equipment with VHF FBFM or single-sideband (SSB) AM equipment. Such a voice
capability is not considered essential for over-ocean ATC purposes and would be possible only
if normal digital ATC transmission were stopped during the voice message. The satellite portion
of ATSAT would not have to be modified to accept FBFM or SSB at a later date, since it is a
frequency translation system capable of handling any form of modulation within its 25-kc band-
width capabilities.

The ATSAT would be placed in a 24-hour equatorial orbit by an Atlas-Agena booster combination. When positioned over the equator at 30°W,[6] it can provide the coverage shown in Figure 4 for satellite number two. It is believed that having ground stations in both North America and Europe would best serve ATC needs (see Appendix B.2). The two ground stations could use the spare channel for inter-station traffic and thus reduce the need for leased lines. The stations would be connected with other ATC centers in their respective areas and would be relatively inexpensive since they would not require tracking antennas.

In order to make use of present aircraft VHF equipment, VHF channels should be used between the aircraft and the satellite. Four 25-kc bandwidth clear channels will be required.

For ATC communications between the satellite and the ground, four 25-kc bandwidth channel assignments in the UHF band of 1540 to 1660 Mc (two at each end) are desirable, but similar assignments in the SHF band of 5000 to 5250 Mc would be an acceptable second choice. Although VHF could be used for this service, it is not particularly desirable, since isolation of the additional VHF antennas would be difficult and additional VHF transmitter power would be required in the satellite (to keep the ground antennas within reasonable dimensions). Furthermore, requiring another four clear channels in the VHF band would be undesirable.

The ground-to-satellite command signals and the satellite-to-ground telemetry data channels used to monitor the satellite require four more UHF or VHF narrowband clear channels.

Clear channels are needed to prevent other services from interfering with system operation. The signal power on the ground from the satellite transmitters is well below the -135 dbw level advised by ITU to prevent interference with ground stations. Signals transmitted from ground to satellite have relatively narrow beamwidth antennas, and the transmission power levels are not over 100 watts.

The estimated costs summarized in Table III are discussed in more detail in Section B.1.4. Because the launch vehicles may be destroyed during launching, and because the satellites cannot be repaired once they are in orbit, the estimates are necessarily based on expected probabilities.

TABLE III. ESTIMATED COSTS OF ATSAT

Ground Station Facilities (2)		$ 2,000,000
Equipment Development (Satellite, Aircraft Antennas)		$ 5,000,000
Initial Year's Vehicle Launch Costs	minimum	$20,000,000
	maximum	$60,000,000
Long-Term Average Cost, Including First-Year Launch Costs		$ 7,100,000/year

[6] This choice is arbitrary and can be adjusted east or west to modify the coverage.
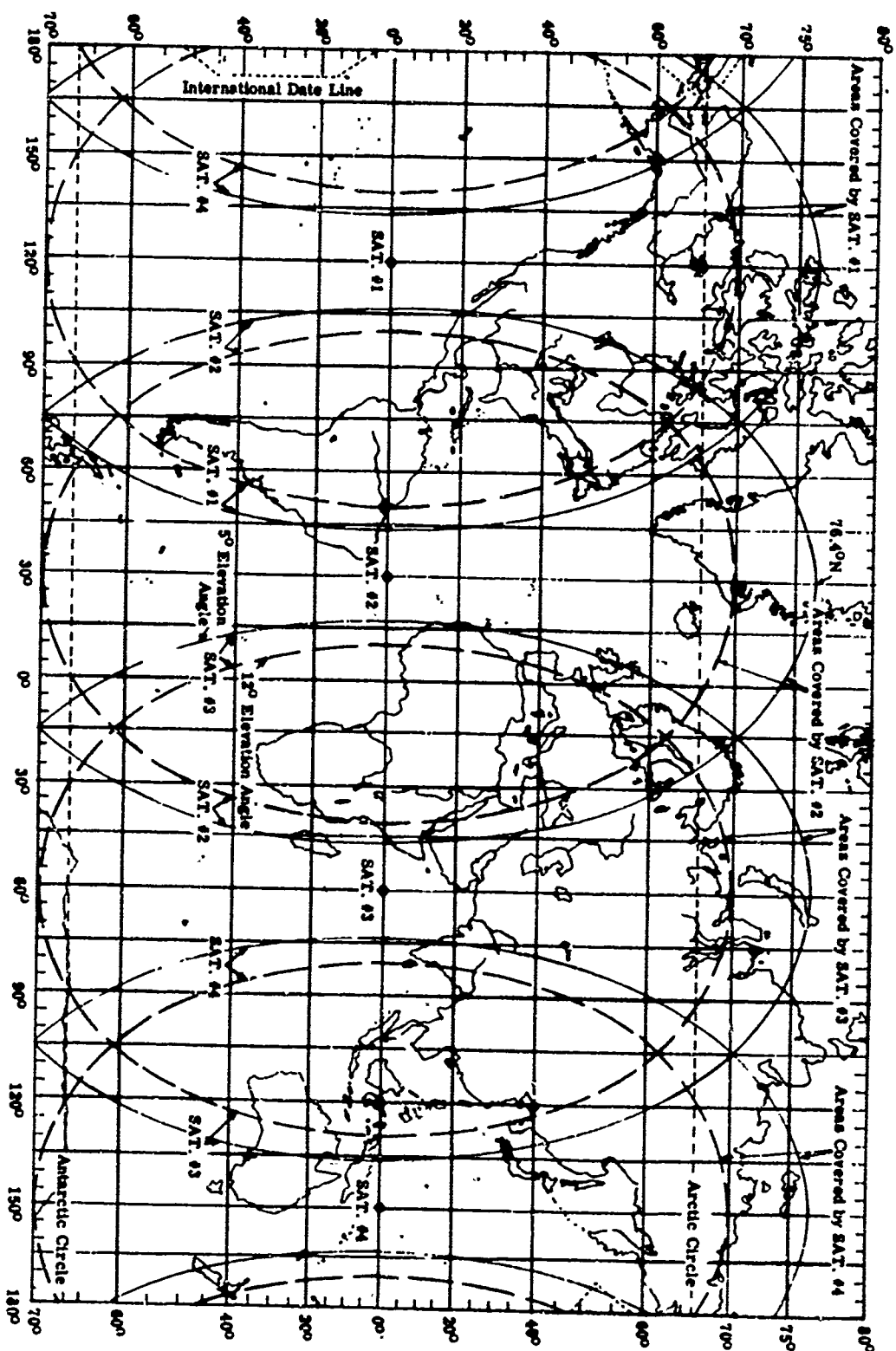
FIGURE 4. AREA COVERED BY FOUR SATELLITES IN 24-HOUR CIRCULAR
EQUATORIAL ORBITS. Ground antenna elevation angles = 5° and 12°.

Fortunately, as launch and satellite technology improve, costs may be considerably reduced. The authors have been conservative in estimating cost and factors that determine it. For example, all of the satellite equipment (with the exception of the antennas) is duplicated, but this duplication has not been taken into account in estimating the expected life in orbit; that is, a conservative value of 5 years has been used.[7]

In spite of the rapid advances in space technology, there are no known developments which may require different choices of frequency or orbit. However, these advances are expected to improve the probability of successfully injecting the satellites into orbit and thus reducing the costs.[8] Also, the eventual development of larger boosters, reusable boosters, and nuclear power sources may reduce costs and provide greater communications capacities as soon as their reliability has been established. Nuclear power sources, which could increase available transmitter power by a factor of at least 10, would also permit the implementation of UHF links between the satellites and the aircraft.

The major costs of aircraft installations for the satellite ATC link are the antenna and the digital print-out or display equipment. The antenna considered is a switched four-blade phased array proposed by Convair [18]. The features of this design (which is used here only for illustration) are similar to ATSAT requirements; costs based on it may be considered representative of retrofit installations. This array is externally mounted; the added drag may be considered excessive, but flush installations on a retrofit basis are potentially expensive and technically difficult. (An alternative external array with lower drag is described in Reference 15; pairs of small elements are mounted on the surface of the vertical fin.) It is assumed that installations on new aircraft would be flush and that costs would be no greater (and quite probably less) than the retrofit costs. The difficulties which may be encountered in supersonic transport installations cannot be assigned a dollar value at this stage. However, ATSAT requirements do not seem to impose any great additional burden beyond that entailed by provision for conventional antennas.

Estimated costs for the four-blade array are:

Materials (antennas, coaxial relays, control panels, casting and individual pre-amps)	$4000
Installation (assuming that work is done during regular overhaul and that no adverse flight characteristic changes are encountered)	$3000
TOTAL	$7000

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[7]Bell Laboratories indicate that a mean time to failure of 10-20 years is required to make a communication satellite relay commercially worthwhile, and they expect to achieve it.

[8]Launching six vehicles whose individual probability of achieving orbit is 0.6 at a cost of $60 million has a 0.95 probability of successfully injecting two satellites into orbit (see Figure 38). If the first two shots are successful, the cost will be minimum. The long-term average is not affected by the initial launch successes.

The question of costs for the digital printer or other input device is much more difficult to resolve. If the over-ocean system is considered independently, there is a wide range of output equipment which could be coupled to the ATSAT output. This might be considered a user's option, and costs would vary widely. However, if it is assumed that a domestic digital system will evolve, the same equipment (perhaps operating at reduced speeds) will almost certainly be used over-ocean.

The functions required are:

(1)	Speed buffer	--	input data rate-to-printer rate
(2)	Printer	--	tape printer (more probably, page printer[9] or possibly a visual display)
(3)	Message composer	--	either an alpha numeric keyboard or a fixed format device for composing messages similar to those in Appendix D
(4)	Outgoing message storage	--	the link data rate and the proposed roll-call system require that outgoing messages be stored, ready for high-speed transmission on command

A system performing these functions could be obtained at a cost of $3000 to $5000 per aircraft.

It has been pointed out that a voice capability would require FBFM aircraft receivers, which are estimated to cost 25% to 50% more than present equipment. The new (conventional) transceiver now coming into use costs approximately $2500.

4.2.2. INTERIM SYSTEM. The interim system will be replaced by satellite relays in approximately ten years. Quick economical implementation of a system which will perform effectively during those years will require:

(a) Choice of a frequency band in which allocations are available for aeronautical purposes or can be obtained with the least international negotiation.

(b) Use of existing aircraft RF equipment or modifications which do not require major expenditures of capital or development time.

(c) Selection of a system in which the interim equipment and the development devoted to it can be used or adapted for use with the eventual satellite system.

A combination of the existing HF skywave system and a VHF tropospheric scatter network meets these criteria.

Although HF skywave is not adequate to meet future requirements alone, it is the best basic propagation mode around which an interim system can be maintained. It is a system in being, and as such provides a basic level of communications immediately. As supplementary service becomes

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[9]The possibilities of voice-to-digital and digital-to-voice conversion are not considered here. Though a great deal of work is being done in this field, there has not been sufficient study of over-ocean requirements to verify the need for voice communications.

available, it will remain the primary means of communication in those areas beyond the range of troposcat. And, finally, when complete, reliable coverage of the North Atlantic becomes available from the first satellites, it will continue to service the operational traffic of the airlines. In addition, it will function as a backup system in the event of VHF equipment failure.

Tropospheric scatter at VHF has a limited range. However, modest expenditures for low-noise receiver preamplifiers[10] and, possibly, improved antennas and transmitters on the aircraft, plus provisions for new VHF ground stations in strategic locations can improve the reliability and add to the channel capacity available with the existing HF system. The same new equipment would insure reliable full line-of-sight communication at the higher jet and SST operating altitudes. Troposcat installations in such major control areas as New York, Gander, and Prestwick would provide the necessary coverage and capacity in those critical areas where traffic begins to converge toward coastal destinations. Additional stations in Greenland, Iceland, the Azores, and Bermuda would further close the coverage gaps.

The supersonic transport will require a reliable high-capacity communication service during acceleration to supersonic speeds; that is, approximately a 400-mile radius about the departure terminal (see Section 3.3). Extended-range VHF could provide this service until satellite relays become available (and after, if the required channel capacity is too high to be accommodated by first-generation satellites).

The fact that the domestic VHF system is relatively satisfactory and that its equipment has been very costly insures its continued presence aboard aircraft. The recommended satellite system operates in the same band. Adopting extended-range VHF as the interim supplement to HF would concentrate technical and financial resources toward a single goal: the development of a unified set of aeronautical RF equipment to serve domestic, coastal and, eventually, mid-ocean areas on a single aeronautical band.

5
SYSTEM CONSIDERATIONS

North Atlantic aircraft, together with oceanic ATC centers and the associated navigation and communication equipment, constitute a man-machine system. As in any such system, the factors affecting performance are interdependent, and changes in equipment or in the standing operation

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[10]Necessarily, aircraft noise must be kept low if full advantage is to be obtained from low-noise receivers. PAA states that during their tropospheric tests the usable gain of 5.5-db receivers was not limited by aircraft ambient noise [11]. Both propeller and jet aircraft were used in the tests.

procedures (SOP) are reflected in the overall operation of the system. For this reason, a proposed change must be analyzed in such a way that the aggregate effect on the system can be predicted with some degree of assurance. This section discusses the general problem of system synthesis and analysis, with particular emphasis on the role of mathematical models.

5.1. THE ROLE OF MATHEMATICAL MODELS

In contrast to the basic scientist, who can measure the effects of a change in a system by experimentation in a controlled laboratory environment, the engineer concerned with large-scale man-machine systems can seldom draw definite conclusions by direct experimentation. An evaluation of the effects of a change in a large-scale system frequently encounters the following types of problems:

(a) The environment in which the system must operate cannot be controlled.

(b) The cost of building and installing prototype equipment for experimental purposes is prohibitively high.

(c) The possibility of endangering lives or damaging property is large.

Because of these limitations and the lack of a general theory for large-scale systems, many analyses in recent years of both military and nonmilitary problems have utilized a class of tools loosely termed "mathematical and computer simulation models." In view of the problem in designing an adequate ATC system for the North Atlantic in which factors such as communication, navigational capability, safety, and economics are considered, mathematical modeling and computer simulation are of considerable interest to the FAA.

From a general point of view, the role of a mathematical model in system design and analysis is to provide a framework for introducing pertinent factors in order to study their effects on overall system performance. For example, the separation standards now employed in the North Atlantic are such that the peak traffic loads predicted for 1975 exceed the saturation point for economic operation.[11] A germane question is: "Can separation standards be reduced to accommodate peak traffic loads within geographical bounds acceptable for economical operation?" Here a model's usefulness becomes apparent. Since the current separation standards are determined by the accuracy of navigation equipment and by the ability of the controller to devise and implement a suitable instruction, a discussion of decreasing separations leads to a consideration of possible improvements in navigation and communications.

The system aspect of the problem is apparent in that, to determine how changes in the communication system might affect ATC, one must have some estimate of the peak loads. But this will be a function of the number of aircraft, the SOP's, the number of channels available, etc. That is to say, the subsystem designers require estimates of usage as inputs in proposing improved systems.

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[11]Note that the supposition of reasonably economic operation is needed; otherwise, by routing aircraft sufficiently far north and/or south, the traffic density can be made arbitrarily small. Clearly, however, a New York-London flight via San Juan or the North Pole can not be considered as economically reasonable.

Mathematical models can represent each part of a large-scale man-machine system, as well as the interconnecting links between subsystems, to a given degree of detail. Further, if the represented relations can be expressed in computable algebraic and logical (Boolean) expressions, the abstract mathematical model can be reduced to a computer simulation model. With such a model, one can introduce various inputs in terms of tables, distributions, and expected values, and simulate the operation of the system. By changing the logical flow of the model, or by introducing different sets of inputs, various alternatives which affect the performance of a given configuration can be compared.

A major difficulty in attempting to develop a communication system for North Atlantic air traffic in 1975 is the lack of a general framework. The lack of concerted effort in characterizing the complete system is particularly critical for two reasons:

(1) The introduction of the SST for air carrier service initiates an era for which there is no comparable operational experience that can be extrapolated from other systems.

(2) Even without the introduction of SST, the predicted increase in the number of flights will saturate the system if operated under current SOP's.

Although one may argue that the airlines and associated organizations were faced with a similar problem prior to the introduction of the subsonic jet, the extrapolation from the current system to a 1975 system appears to be much more difficult.

In the past, a number of attempts have been made to describe certain aspects of North Atlantic ATC operations by modeling techniques [2 and 19]. It does not appear that the studies have dealt adequately with the interaction between the navigation system, the type of ATC system (i.e., strategic, tactical, or hybrid), and the communications system. Since the cost and difficulty of supplying communications to an aircraft over the North Atlantic is a sensitive function of these factors, the effects of system interactions cannot be neglected. A systems analysis should be initiated as soon as possible to provide the essential framework for more detailed communication system design.

30

Appendix A
GENERAL PROPAGATION BACKGROUND

This appendix is a compilation of pertinent background material from the literature. It is hoped that it will eliminate the need for much of the tedious reference searching which would otherwise be required for the more serious reader.

A.1. PROPAGATION OVER THE NORTH ATLANTIC

Radio communications over the North Atlantic are complicated by the following features: (1) the northernmost areas fall within the auroral zone where there are high attenuations in the ionosphere; (2) the southernmost areas are not far enough south to benefit from the low-loss ducting phenomena, which are fairly dependable at the southerly latitudes, but are close enough to some of the principal noise centers to increase the atmospheric noise received; and (3) dependable long-distance (1300 miles or more) communications are desired. These limitations, added to the problems which are normally encountered in aircraft communications, such as limited antenna gains and transmitter powers, and aircraft noise, make it necessary to examine the various possible modes of propagation which might be useful, not only by themselves but in a combined, or hybrid, system.

In general, the radiation from an antenna in the presence of a ground plane can be described in terms of two components: the surface or groundwave, and the spacewave. The groundwave is modified by the effects of a lossy ground plane. The spacewave follows a direct, line-of-sight path, but is limited to the horizon unless it is returned to the earth through a reflecting mechanism. Some of these mechanisms are fairly continuous and well defined, such as the "bounce" off the ionosphere at high frequencies and refraction in the troposphere. In addition, there are several sporadic mechanisms giving intermittent signals well beyond the line of sight: (1) changes in the slope of the refractive-index profile of the troposphere which cause super-refractive conditions (e.g., ducting), (2) sporadic clouds in the E region of the ionosphere, (3) turbulent layers in the ionosphere, (4) meteor-induced columns of ionization at heights of 70-110 km, (5) auroral ionization, and (6) normal F-layer propagation at lower VHF during abnormal solar conditions.

Propagation thus depends heavily upon the characteristics of the earth and its atmosphere. This dependency requires considerations of frequencies, polarizations, regions of operation, and even the time of day and year. Therefore, approximations and generalizations are necessary in the following summary.

A.1.1. SKYWAVE.
The spacewave encounters the earth's atmosphere and, therefore, is highly dependent upon the characteristics of the atmosphere. Figure 5 shows some of these characteristics with the commonly used designations for the various layers. The direct part of the spacewave represents energy that travels from the transmitting to the receiving antenna in the earth's troposphere. This wave commonly consists of at least two components: one is produced by a ray
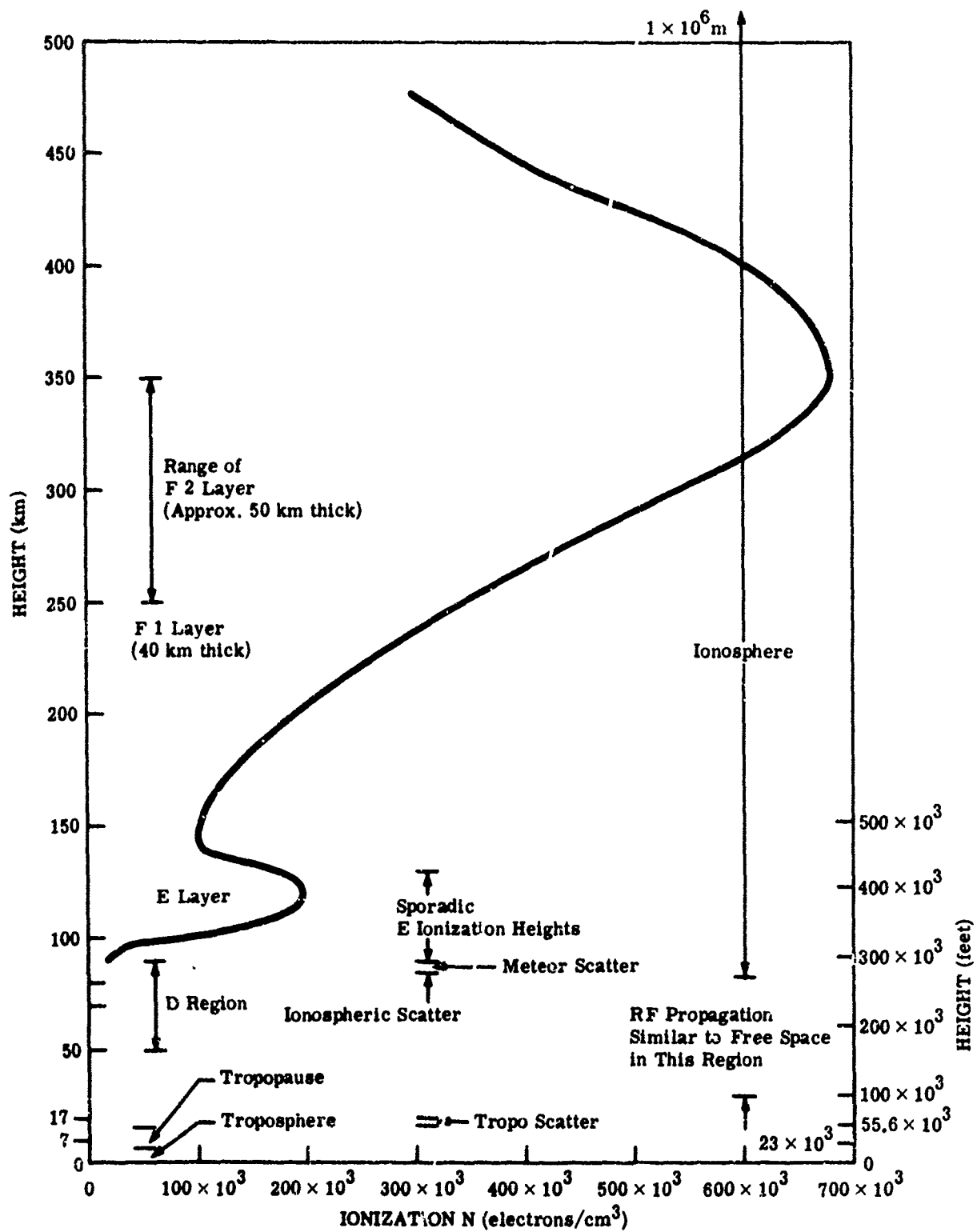
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FIGURE 5. IONIZATION OF EARTH'S ATMOSPHERE [20]

that travels directly from transmitter to receiver, and the other by a ray that is reflected to the receiver by the earth or other objects. The net-received signal is the vector sum of the two components. The mode of operation using the spacewave is known as skywave reception. Skywave reception is made possible by the ionization in the upper atmosphere, which begins about 80 km above the earth's surface and which bends the ray path toward the receiving antenna.

The ionosphere influences radio waves largely through the presence of free electrons. Heavy positive ions are present also, but their effects are negligible above frequencies of a few hundred cps. The layers of the ionosphere are referred to as the E, F_1, and F_2 layers, as shown in Figure 5. A lower layer, D, is also present during the sunlit hours, but its principal effect is to absorb rather than reflect energy.

In the ionosphere, the electric field of the wave exerts a force on the free electrons. These electrons, in turn, act as miniature dipole antennas, re-radiating with a phase displacement. This action, together with the change in the electron density (the density varies as a function of height in the ionosphere), produces an effect on the wave equivalent to that of a varying index of refraction bending the ray paths downward again. The magnitude of the electron current induced is greater at lower frequencies (the average velocity induced in the electrons by the radio wave is inversely proportional to frequency) so that refraction is more effective at lower frequencies.[12] In fact, below about 50 kc the ionosphere can be closely approximated by a sharply defined reflecting boundary. As the frequency is increased, a critical frequency is attained above which the radio waves are propagated through the ionosphere and into outer space. This critical frequency f_c is defined so that a wave of the critical frequency or lower will be reflected from the ionospheric layer irrespective of the angle of incidence. Waves having a frequency greater than this critical value will be returned to earth only when the angle of incidence is sufficiently low.

If a wave with frequency greater than the critical frequency is propagated at different angles of incidence, a minimum distance is reached. (The skip distance corresponds to the maximum angle of incidence which will still return the incident wave to earth.) The frequency which makes a given receiving point correspond to a distance from the transmitter equal to the skip distance for that frequency is termed the maximum usable frequency (m.u.f.). For a simplified plane model of the ionosphere, the m.u.f. is given by f_c sec ϕ, where ϕ is the angle of incidence at the reflecting layer. Predicting the m.u.f. for an actual situation is much more difficult. For practical cases the m.u.f. does not exceed about three to four times the critical frequency (the maximum theoretical value of sec ϕ is about five). This limits the one-hop transmission path to a maximum of about 2500 miles. The transmission via the E and F layers is essentially that of free space (within about three db at the m.u.f.). Methods for predicting the m.u.f. from ionospheric data have been developed, and forecasts are published regularly by the NBS.

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[12] The earth's magnetic field causes the electrons to describe elliptical paths instead of simple oscillations in the plane of polarization. The net effect is that polarization is not maintained in ionospheric transmission. This effect is also inversely proportional to frequency.

33

The range of the critical frequency between nighttime and daytime operation is about a factor of three (higher for daytime operation). However, during the daytime a gap appears in the usable frequency spectrum between approximately 0.5 and 1.5 Mc. This is caused by absorption of the skywave in the D region of the ionosphere. In the nighttime skywave spectrum there is no gap.

The upper parts of the ionosphere are subject to great variations caused by disturbances from various sources. Measurements at HF have indicated that under quiet conditions (no ionospheric storms) there is very little difference between transmission over an auroral and non-auroral path [21]. Also, when aurora are present near the zenith, there are strong reflections from sporadic E clouds in the ionosphere at frequencies above 7 Mc [22].

Ionospheric storms are disastrous to skywave communications at HF [23]. These storms generally occur in phases. In the first phase, high turbulence in the auroral regions (near the magnetic poles) causes complete failure of HF skywave communications and weakening of nighttime MF (broadcast-band) skywave. In the second phase, the effects of the storm expand and diffuse toward lower latitudes; there is a decrease in the m.u.f. and an increase in the absorption at high frequencies. Mild storms may cause blackouts in localized areas, particularly in the equinoctial periods. Great storms, which tend to occur on the rising part of the sunspot cycle, can adversely affect skywave communications, even at relatively low latitudes. An important point is that these storms occur in phases, and that these phases affect localities and frequencies at different times [24]. Thus the effects of these disturbances can be minimized by using a combination of space and frequency diversity, by providing alternate routes, and by using the best frequency within the available HF band in each locality. Such an approach was suggested in the literature after field tests in the Arctic showed that some HF communication circuits stayed open during disturbed periods [8].

The hypothetical system proposed in Reference 8 uses transmitting and receiving stations placed at the vertices of an array of equilateral triangles. The spacing between stations is about 1750 miles. From the study of this theoretical system, it was concluded that communication within and from the polar regions is nearly always possible (approximately 90% of the time), even during "p .ar-cap blackout," when a number of alternate frequencies and both frequency and space diversity switching are used.

Another ionospheric disturbance which can be severe occurs as a result of a large solar flare. This produces complete HF blackout on paths traversing any portion of the sunlit part of the world. These blackouts can occur at any time, but are particularly likely to be serious during the rising part of the sunspot cycle. They are characterized by additional path losses of fifty to hundreds of db and have been known to last many hours. However, total radio-circuit time lost may be only a fraction of a percent when averaged over several years.

Normally, frequencies below the broadcast band are not severely affected by disturbances of this type, and propagation at LF and VLF may actually improve during such a disturbance because of the increased conductivity of the lower part of the ionosphere. Also, since most of the at-

mospheric noise in the North Atlantic is propagated by the ionosphere, higher ionospheric attenuation results in a lower noise level.

So far, this appendix has considered the effects of the E and F layers, which are responsible for the refractive effects of radio waves. However, most skywave absorption takes place in the D region. This type of absorption is called non-deviative since the ray passes through the absorbing region rather than being bent to earth by it. (Some energy absorption also occurs in the region where the wave is bent to earth by deviative absorption; the absorption increases with the amount of retardation of the wave. However, deviative absorption is small compared to D-region, non-deviative absorption.) Non-deviative absorption when expressed in db, has been found to be approximately inversely proportional to the square of the frequency (see Appendix A.1.5). It follows that HF skywave signals are stronger for frequencies close to the m.u.f. Unfortunately, as one operates closer to the m.u.f., communications become less reliable. Unless one is willing to test the channel before each use and to employ several alternative frequencies, the use of the high end of the HF band presents a rather formidable challenge for reliable operation.

Another consideration is the noise present in the MF and HF bands. In the MF band atmospheric static is ordinarily the controlling noise effect. Atmospheric static is caused by lightning and other natural electrical disturbances and is propagated over the earth by ionospheric transmission — the same mechanism as described above for signal propagation. Atmospheric static is more noticeable in the warm, tropical areas, where thunderstorms are frequent, than in the colder, northern regions. A typical range of noise values averaged over a year is about 30 db higher in the tropics than in the Arctic region, with the noise level at 40° latitude around the median value (in db) between these extremes [25]. The static-noise level follows roughly the same frequency dependency as does ionospheric propagation with the static level stronger at night than in the daytime, up to about 30 Mc, and takes a characteristic dip of about one to two Mc at noon. Estimates of atmospheric noise on a world-wide basis are available [26]. At the upper end of the HF band, cosmic noise becomes the controlling factor, but since this is much lower than atmospheric noise at the lower frequencies, it follows that the closer the operating frequency is to the m.u.f., the lower the noise level. Below the m.u.f., of course, only a portion of the cosmic noise reaches the earth. Man-made noise may become significant near large cities at the higher end of the HF band. In addition, the electrical noise generated by the aircraft must be considered.

Aircraft antenna problems are not severe in the HF band, but as the frequency is lowered through the MF band it becomes increasingly difficult to achieve good antenna efficiency [27, 28]. If a directive radiation pattern is not required (most often it is not, since the direction of the maximum received signal is expected to vary with reference to the airframe), the lower frequencies yield good overall patterns below about six Mc. Above this value and up to the upper end of the HF band, patterns are well-behaved, becoming more directional in the VHF range. The major dimensions of typical transport aircraft are of the order of a wavelength for the 3-30 Mc range, so that the wings and fuselage can serve as excellent radiating elements when appropriately excited. The major dimensions of future aircraft are expected to remain in this same range.

The aircraft antenna problem at HF is complicated by the frequency sensitive characteristics of ionospheric propagation. It is customary to provide a range of operating frequencies. This, together with aircraft resonance, causes the antenna impedance to vary from inductive to capacitive. An antenna tuner is required to match the antenna for good power transfer. Current aircraft systems incorporate automatic matching, so that with careful antenna design this problem is not severe. However, additional equipment is required. Though polarization on a typical aircraft antenna varies with the operating frequency, this does not hamper reception of the skywave since signal polarization is not maintained in this mode of propagation.

Precipitation noise in aircraft is a major problem; unless it is attenuated, it can be greater than atmospheric static [29]. Moderate design precautions can reduce the noise caused by precipitation static to the same order of magnitude as atmospheric static at MF. Although the precipitation static falls off with increasing frequency, it does so less rapidly than atmospheric static, so that the effect of precipitation static is still present in the HF band. This precipitation static occurs in the electrostatic field about the aircraft; consequently, reception by a loop antenna is advantageous at the lower frequencies. Such LF loop antennas are used on present aircraft as one of the elements of the ADF system. They could also be used on any LF communications channel that is proposed for aircraft communication (for reception only — this is discussed further in the next section).

Multipath conditions for skywave propagation are severe. Two problems arise: (1) the fading which results from RF carrier phase differences, and (2) delays in the arrival of the signal due to propagation via several paths. These delays may be of the same order of magnitude as spoken syllable lengths. Tests made on HF circuits indicate that delays up to several msec between different paths can be expected, so that there is distortion even on voice circuits [30]. The multipath fading is fairly rapid; thus, if there is enough redundancy in the message, a given message gets through in spite of the multipath condition. Digital rates higher than about 10^3 pps do not appear feasible in skywave communication. In order to minimize the effects of multipath conditions, operation at frequencies close to the m.u.f., frequency shift keying (FSK) with long keying elements, and directive antenna arrays could be employed. The use of alternative routes and increased power has little, if any, effect on multipath jitter.

At the frequencies most suitable for long-range transmission (i.e., close to the m.u.f., at low angles) the skip distance is quite large. As the frequency is lowered, the groundwave and skywave ranges overlap, with the result that severe fading can occur when the two signals are comparable in amplitude. If transmission by both waves is desirable, it may be advantageous to use two transmitter (and/or antenna) sites and switch between them as the conditions dictate.

A.1.2. GROUNDWAVE. If a radio wave is radiated near the earth, some of the energy is transmitted into the ground. Since the ground is not a perfect reflector, this energy sets up ground currents, and the resultant waves propagate. In carrying this induced current, the earth behaves as a leaky capacitor, described in terms of the conductivity and dielectric constant. The losses of energy in the groundwave from absorption by the earth are replenished, in part, by the diffraction of additional energy downward from portions of the wave that are immediately above the surface of the earth.

36

The groundwave is vertically polarized near the earth since any horizontal component of the electric field in contact with the earth is effectively short circuited. However, as the antennas are raised above the ground, the strength of a horizontally polarized component for a given radiated signal increases much more rapidly than the strength of the corresponding vertically polarized component, until the antennas reach a certain height, above which the field is substantially independent of polarization. (The height is highly dependent on the frequency: at the frequency of 3 Mc, it is about 6000 feet; at 30 Mc, 250 feet; and at 300 Mc, 10 feet.)

The propagation of the groundwave depends primarily on the conductivity and dielectric constant of the earth, the frequency, and the number of wavelengths from the receiver to the transmitter and to the surface of the earth. The groundwave attenuation is essentially that which results from a plane, perfectly-conducting earth out to a distance of about $100/(f)^{1/3}$ miles, where the frequency f is in Mc. For example, this distance for one Mc is about 100 miles.

When both antennas are within a wavelength of the surface, losses for groundwave propagation depend primarily upon the distance between the antennas. Near the transmitting antenna, the losses in the earth have little effect on the strength of the groundwave, and the resulting decrease in the field strength is nearly proportional to the distance. At distances greater than about ten wavelengths the propagation losses have increased. The field strength of the groundwave becomes nearly inversely proportional to the square of the distance when a plane earth is assumed. Beyond the distance at which the plane earth assumption is valid, the reduction in field strength below the free-space value is caused more by curvature than by ground losses. Curves for the expected transmission losses have been published by the National Bureau of Standards and take into account such factors as the earth's curvature [31]. A typical set of these curves, taken from Reference 31, for field strength obtained with a single, short, vertical antenna (short compared to one wavelength) is shown in Figure 6 for propagation over good earth and in Figure 7 for propagation over sea water. These losses approach an exponential form as the distances increase.

The curves for propagation over earth vary widely according to the terrain, whose conductivity varies over at least one order of magnitude. However, the conductivity of sea water does not vary appreciably, so that the basic transmission loss of the groundwave is fairly constant. An exception occurs when ice is present in the path of the groundwave. Reductions in field strength as great as 60 db have been reported at 2 Mc when a 350-mile propagation path over ice was compared with the same path over sea water [32].

Because the transmission losses over a land path are large, antennas for communication over sea water should be placed as close as possible to the water's edge. Signals radiating from an antenna located only a few miles from the water can suffer an additional loss of about 10 db from the intervening ground.

When the airborne antenna is any appreciable distance above the ground, the signal strength increases. One may think of this height gain as being associated with the increase in the radial line of sight, although this height-gain factor applies even within the shadow range. (This same effect is illustrated by the diffraction of light by a knife edge.) The field strength is thus the result of the increased line of sight plus the diffraction effect beyond the horizon.
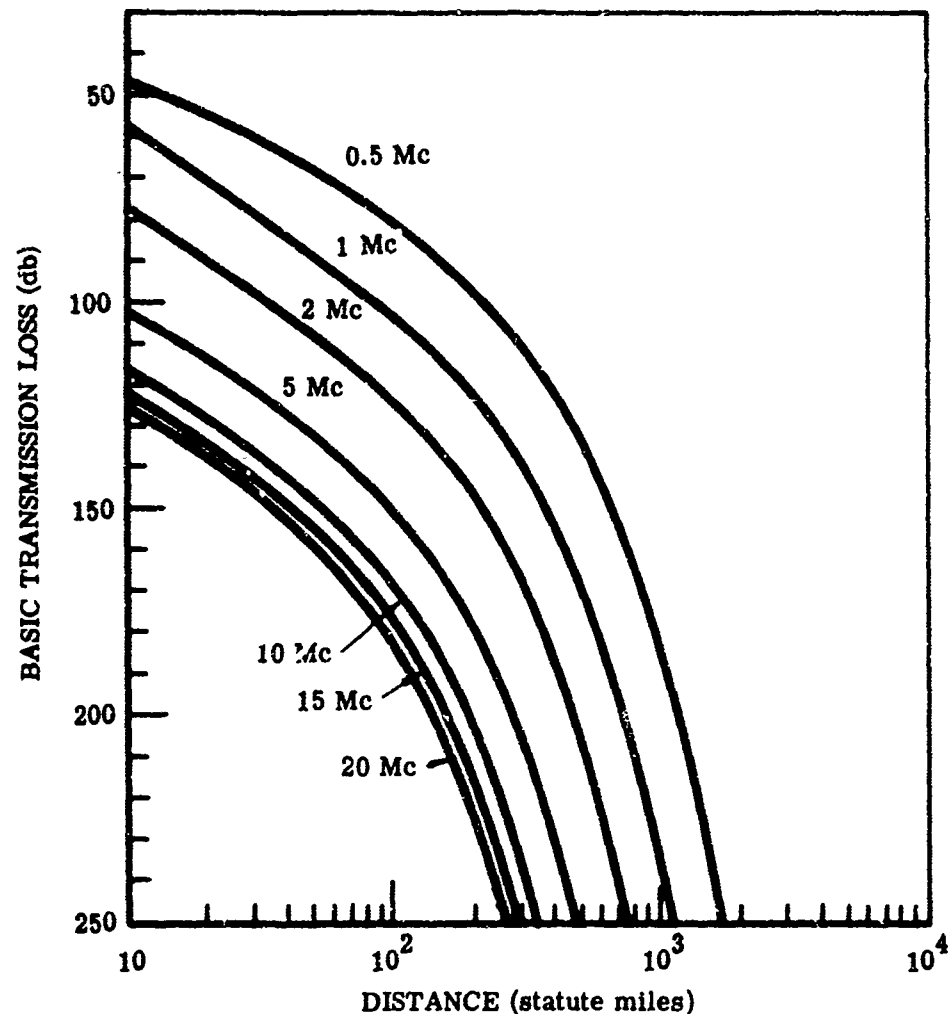
37

FIGURE 6. BASIC TRANSMISSION LOSS FOR VERTICALLY-POLARIZED
GROUNDWAVE OVER GOOD EARTH

The gain in signal strength with increasing height follows a definite pattern (see Figure 8): it begins at zero height with a value of unity and zero slope, goes through a dip or minimum which is dependent upon the wavelength and the earth's constants, and then increases linearly with height. In the region where the signal strength increases, the polarization is predominantly vertical and the signal field strength depends somewhat on variations of station height. Above a few Mc and a height given approximately by $30 \lambda^{2/3}$ over land, and $30 \lambda^{2/3} + 3.0 \lambda^{4/3}$ over sea water (both the height and λ are in meters), the height gain increases rapidly (exponentially) and within several hundred feet the variations in station height become unimportant [33]. For three Mc, this "critical" height (i.e., the height with respect to a ground level station) is about 6500 feet, so that the altitude used by jet aircraft becomes a definite advantage. This simplified approach demonstrates that the height gain becomes more important at higher frequencies, although the exact dependency is not straightforward.
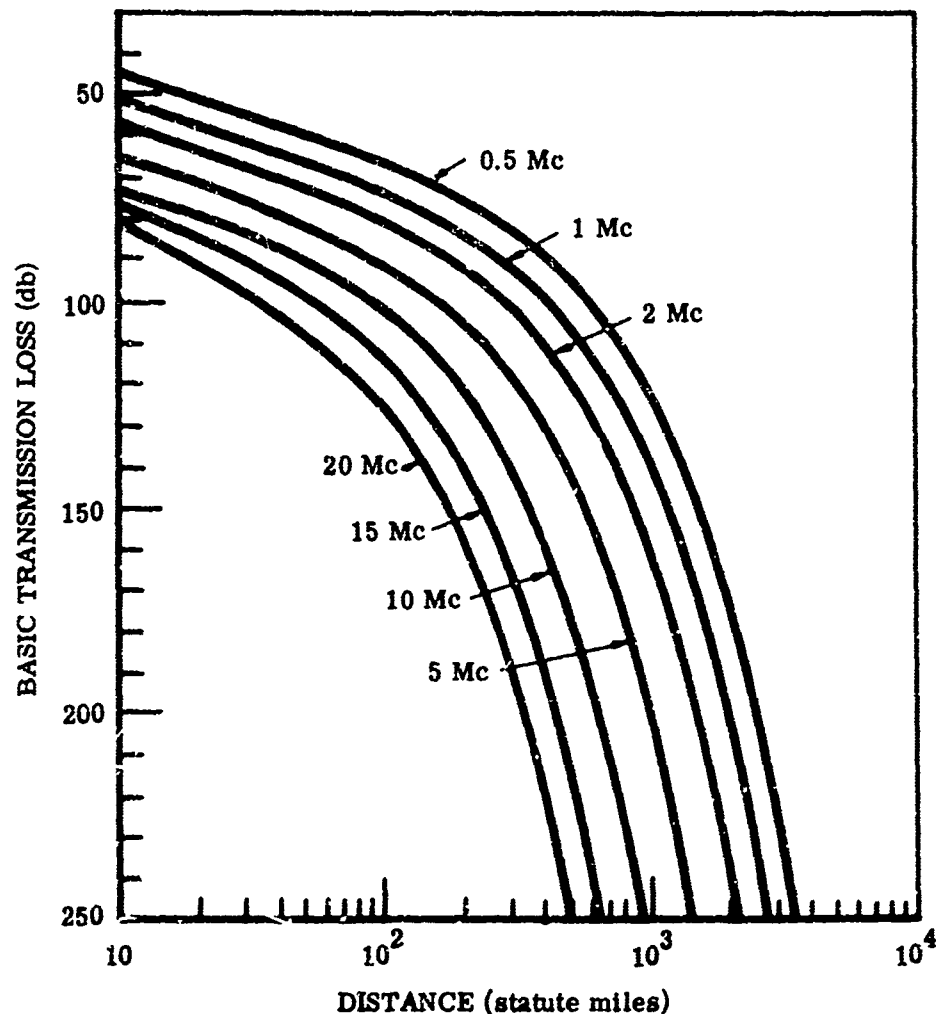
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FIGURE 7. BASIC TRANSMISSION LOSS FOR VERTICALLY-POLARIZED
GROUNDWAVE OVER SEAWATER

Height-gain curves in db (calculated values), plotted as a function of altitude, are shown in Figure 8. The curves are for a ground station at zero elevation. Apparently there have been few, if any, experimental height-gain measurements in the frequency, altitude, and distance ranges of interest; consequently, these computed values are the only ones available [34].

The received noise consists mainly of atmospheric noise propagated in the ionosphere, atmospheric noise propagated in the groundwave, and man-made noise. If the aircraft is not near a heavily populated area, the latter can be disregarded. Internally generated noise (within the aircraft), and precipitation static scan usually can be reduced to acceptable levels by careful application of noise suppression techniques. The atmospheric noise propagated in the groundwave is appreciable only if a thunderstorm is located within a few hundred miles of the receiver. The three principal centers of atmospheric noise are North Africa, Central and South America, and the East Indies. In addition, there is a region of activity in the doldrum belt about the
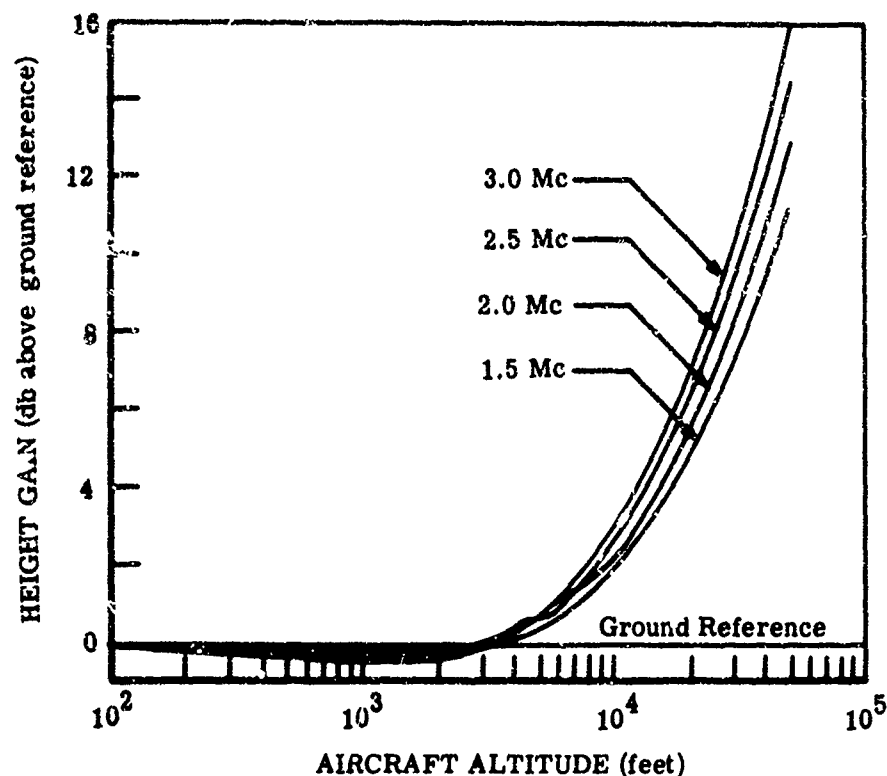
FIGURE 8. HEIGHT GAIN FACTORS IN THE MF BAND FOR A TRANSMITTER AT
THE GROUND REFERENCE LEVEL

equator. However, the North Atlantic is at least 1000 miles from any of these principal noise
centers. This, together with the fact that thunderstorms over the ocean are relatively rare,
indicates that atmospheric noise arriving via the groundwave is quite low and can therefore be
eliminated as a controlling factor in communications. Therefore, the atmospheric noise propa-
gated by the ionosphere is the main source of noise present in the groundwave signal. Since
this noise arrives at the antenna from a skyward direction, it suffers no ground attenuation
effects and is independent of receiver height; consequently, the overall S/N can be expected to
increase with the height-gain factor.

Propagation by the skywave may become very poor during periods of high ionospheric absorption
(corresponding to solar flares, etc.). At such times, the received noise from atmospherics propa-
gated by the skywave drops while the groundwave signal intensity remains normal. The result is
a gain in the S/N just when reception of the skywave may be completely "blacked out." For this
reason the use of the groundwave in the MF and low HF bands to reinforce the present long-range
HF communications has been suggested [35]. Because of the ionospheric absorption maximum in

40

the region of one to two Mc during the day, the noise level is particularly low in this region; therefore, groundwave propagation can be used to advantage where the field strength is sufficient to provide communication in the presence of receiver noise (including aircraft noise).

The fading problems accompanying groundwave propagation were discussed in relation to sky-wave propagation and are generally serious in the region where both the skywave and the ground-wave are present with about the same field strengths.

One of the main problems in the use of groundwave propagation is the choice of an operating frequency that is low enough to achieve sufficient signal strength but high enough to benefit from decreased atmospheric noise levels. In addition, aircraft antenna efficiencies decrease at lower frequencies, and the height-gain factor becomes more pronounced at higher frequencies. Therefore, with the introduction of traffic at higher altitudes, groundwave propagation at HF becomes more attractive. It would be particularly useful for filling the gaps in coverage near the station caused by skywave skip.

Tests using groundwave propagation have been performed at 2.9 Mc with reasonable success [35]. The data were taken in propeller-type aircraft, so that the advantages of height gain were meager. The tests, conducted under minimum expected noise conditions, showed that signals would be trans-mitted over distances of 500 to 600 miles between aircraft and ground stations. Actual opera-tional conditions would introduce two opposing tendencies. The presence of static and distant signal interference would tend to reduce the range. On the other hand, one would expect the transmission range to increase at typical jet altitudes. Quantitative statements about the probable operational coverage could be given only in statistical terms.

The airborne transmitting antenna problem effectively precludes air-ground transmission via groundwave at LF, and it remains a problem throughout the MF band [36]. It is difficult to radi-ate much power from an antenna whose physical length is below one-eighth of a wavelength even when loading elements are used. When the signal is radiated from the aircraft antenna, the horizontally polarized component "sees" the ocean as a nearly perfect conductor and is reflected while the vertically polarized component propagates by the groundwave mode. Thus, it is important for aircraft antennas to have a strong component in the vertical plane. Most HF antennas used on present over-ocean aircraft do have appreciable components in the vertical direction, even though the antennas are designed for good coverage with horizontal polarization. Thus both sky-wave and groundwave modes can be accommodated by a single HF antenna — though neither will be optimum.

Increasing the sensitivity of the ground receiver system can reduce the effects of a low effective output of an airborne transmitter. For operation in the northerly latitudes, an ef-fective method of reducing the noise and increasing the directivity is to use an array of antennas (i.e., at least two) to reduce the sensitivity to atmospheric noise propagated from the southerly latitudes.

Since the propagation losses are low and the coverage and reliability are excellent, LF groundwave propagation appears to be desirable. The antenna problems are not severe for a ground

station; thus it is possible to use LF for a one-way ground-air communications link. Although frequency allocations are difficult to obtain in the LF band, and maximum bandwidths are limited to a few hundred cps, the advantages of LF have prompted the installation of a meteorological information service using teletype in the North Atlantic. Highly reliable coverages of 900 to 1200 miles have been obtained in this manner by means of ground-station powers of about 2 kw and loop antennas on the aircraft [37].

A.1.3. SCATTER. Propagation by means of scattering mechanisms is briefly discussed below with some of the experimental results which have been reported in the literature.[13]

A.1.3.1. Tropospheric Scatter. By means of tropospheric scatter, dependable radio transmission is possible beyond the radio line-of-sight. The scatter is forward since the signal strength drops off rapidly as the scatter angle θ is increased. A geometric sketch of a tropospheric scatter system is shown in Figure 9.

Several theories have been proposed to explain the persistent long-distance VHF-UHF-SHF tropospheric phenomenon. The theory which has been given the most attention is that of turbulent scattering. This theory assumes temporal and spatial fluctuations of the refractive index in the common volumes illuminated by the antenna beams. The theory has been modified to include layers of different refractive index [38]. Theoretical work continues to grow toward an ability to predict the actual field strengths.

Tropospheric scatter predominates in a region that begins where the scatter produces a field equal in strength to the diffracted field.

A graph for finding the path loss for tropospheric scatter is given in Figure 10. A reliability margin is included to account for the fading on the circuit. The losses shown are caused by the scattering mechanism; losses from free-space propagation must be added to the results of Figure 10 to obtain the overall loss. The available power F_a (in dbw) from a receiving antenna can be found as follows:

$$P_a = P_t + G_t + G_r - L_f + L_{BH} - L_t \tag{1}$$

where: P_t = the transmitter power above one watt

G_t and G_r = the transmitting and receiving antenna gains, respectively (db)

L_f = the free-space propagation loss (db)

L_{BH} = the median beyond-the-horizon loss (db)

L_t = the terminal loss (db)

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[13]The true mechanism of tropospheric scatter and the exact nature of the functions and constants to compute path attenuation from frequency, antenna gains, distances, altitudes and observable atmospheric conditions is still controversial. Since a sufficient sampling of experimental data is not available as yet for conditions applicable in this study, the full and reliable geographic coverage to aircraft to be expected from a ground station can only be conjectural.

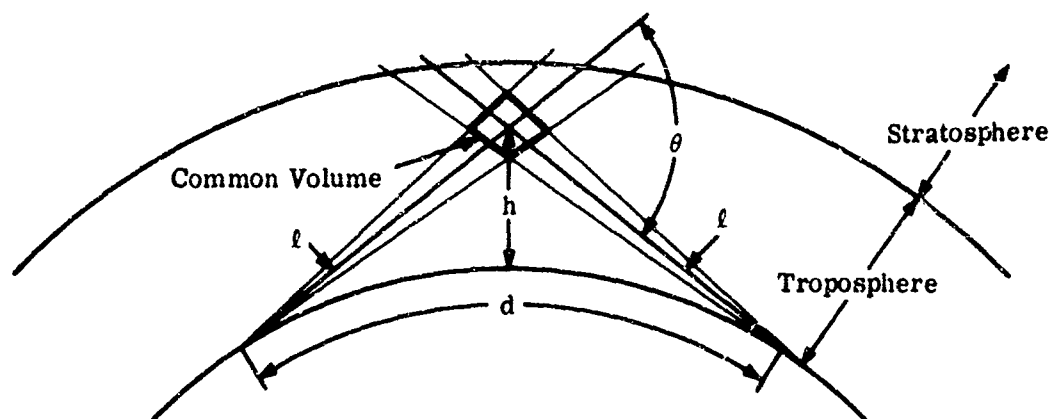FIGURE 9. GEOMETRY OF TROPO-SCATTER. θ = scatter angle, h = altitude
(60,000 to 70,000 feet or 18 to 21 km), d = great-circle distance between stations,
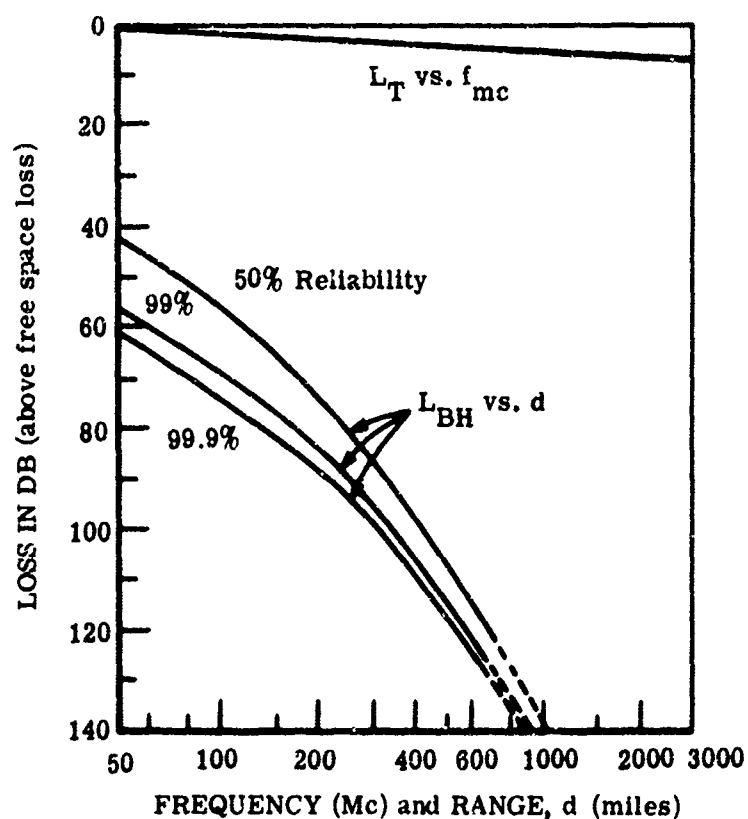ℓ = ray distance.

FIGURE 10. MEDIAN BEYOND-THE-HORIZON LOSS IN TROPOSPHERIC SCATTER
PROPAGATION [39]. L_t = terminal loss = $5 \log f_{Mc}$ - 10 db, L_{BH} = median beyond-
the-horizon loss in db.

One of the causes of the variability of tropospheric scattering is the change in the mean climatic conditions of the troposphere, as a function of season and location. Warm tropical air masses over the ocean minimize path losses; cold, stagnant, dry Arctic air masses maximize them. Median path losses between these two extremes can differ by 30 db. In fact, conversations with Pan American Airways personnel indicate that at times there was no observable evidence of tropospheric scatter in the Frobisher Bay region ($68°$ W, $64°$ N) and in the Near East over deserts. (No substantiation from other sources is available on this point.) Seasonal variations of 20 db have been measured, but these variations become less noticeable as the circuit length is increased.

The signal amplitudes that result from tropospheric scattering show a rapid, deep fading. This fading results from the effects of several changing path lengths and can be reduced by diversity and pattern changes. The fast fading follows a Rayleigh distribution. In general, it has been found that a 20-db fade can be expected about 1% of the time [40]. The average length of a rapid fade is about one second at VHF. Slow fading occurs over several hours and is almost independent of frequency. This slow fading follows a normal probability with σ about 8 db and results from the changes in the average refraction in the atmosphere [40].

Antenna gains normally are stated with the assumption of a plane wave arriving at the antenna's angle of maximum response. In tropospheric scatter there is an angular spectrum at the antenna; if the solid angle subtended by the received signal is greater than the antenna lobe, the power collected will not increase as a linear function of effective antenna area. In other words, very-high-gain antennas may not be as efficient as they appear in tropospheric links. This aperture-to-medium coupling loss introduces the factor L_t in loss calculations. The strongest signals are obtained by aiming antennas at the horizon along the great-circle route between stations. Height gain is realized until the bottom of the antenna is about 20 wavelengths above the ground [41]. An unobstructed path to the horizon is required. Nearby electrical noise can adversely affect reception.

Tropospheric circuits have been engineered from 100 Mc to several Gc. Operating at the higher frequencies has several advantages: (1) losses are not extremely dependent on the frequency, (2) allocations are easier to obtain, (3) large antennas are required to obtain high gains at low frequencies, and (4) the cosmic noise decreases at about 7 db per octave. However, this last effect can be disregarded above 500 Mc because receiver noise becomes the controlling noise factor at about that level (as shown later in Section A.1.5).

The bandwidth is limited by the multipath; delays of short pulses have been measured up to 2×10^{-6} seconds over a 618-mile path [41]. Multipath effects can be lessened by making the antenna beam smaller than the cone of scattering angles. A bandwidth of a few megacycles over distances of about 100 miles beyond the radio horizon is feasible.

Pan American World Airways has developed and tested a tropospheric scatter system on its air-ground networks [11]. Using the VHF band, the ground stations were at sea level and the aircraft at flight levels above 14,000 feet. With a ground station near Shannon, Ireland, it was found that for aircraft below 24,000 feet, the mean communication distance beyond radio line-of-sight was about 154 miles (ranging from 76 to 226 miles); for aircraft above 24,000 feet the

44

improvement over radio line-of-sight was only 138 miles (ranging from 11 to 226 miles). No special equipment was used in the aircraft.

Tests using the VHF band (128.1 Mc) were also made from a site at San Francisco. One conclusion was that for flights at 28,000 feet and above, the range exceeded 600 miles about 90% of the time. The extreme ranges are attributed to favorable climatic conditions and to the ducting prevalent in the area. The distinction between ducting and true tropospheric scatter must be strongly emphasized. Ducting is a waveguide phenomena wherein the signal is propagated between anomalous layer structures in the atmosphere. Their occurrence depends upon an unusual combination of meteorological conditions. While ducting is fairly common in some areas — usually relatively warm, humid climates — there is no known area where they can be considered the basis for a highly reliable ATC communication system. In the North Atlantic occurrences are infrequent.

The ground station site for a tropospheric scatter link should be located so that the optical horizon angle is as low as possible and the ground antenna gain as high as possible. Horizontal beamwidths may have to be greater than the vertical beamwidths. Stacked elements are required to give a small vertical angle. Off-path scattering must be confined to an angle of 4° at a 200-mile range [42]. Present aircraft antennas (quarter-wave stubs) have gains in the 2-db range. (Gains in some directions may be as much as 15 db below that of an isotropic radiator.)

One possible objection to a purely tropospheric system is that its limited range makes it of small value in a large region such as the Pacific. Both military and international carriers would object to a system which is workable only on a regional basis. However, tropospheric scatter could be used in a hybrid system to overcome this objection (e.g., in conjunction with a satellite system).

The FAA's experimental extended-range VHF link between Cape Cod, Massachusetts, and San Juan, Puerto Rico, is of interest here [13, 14]. The ultimate goal of the experiment is the complete coverage of the New York-to-San Juan air route with one link. The system employs ground transmitters of relatively high powers (4 kw), high-gain antennas (24-db transmitting, 33-db receiving), and low-noise aircraft receivers.

The U. S. Air Force also has implemented an experimental tropospheric scatter link for Military Air Transport Service (MATS) flights between Goose Bay, Labrador, and England. One voice channel is provided at 300 Mc. One-kw transmitters are used on the ground and the aircraft. Dual stacked-log periodic arrays are employed to provide 18 db of gain and diversity. A low-noise preamplifier was used in the aircraft.

Both the FAA and USAF systems are just beginning to receive first results. Ranges of 500 to 600 miles have been achieved on both systems, but it is not yet known whether these ranges are reliable or anomalous. Further results should be available soon.

A.1.3.2. Ionospheric Scatter. Propagation by ionospheric forward scatter takes place in the upper D region of the ionosphere. The scattering phenomenon occurs at frequencies well above the m.u.f. of skywave reflection for the distances involved. Reflections consistently occur at

45

about 85 km, although they may occur at other heights and may vary with the time of the day and year. The typical received signal consists of two types: slowly fading, continuous signals, and rapid bursts of higher energy signals. The latter is usually disregarded in the design of an ionospheric scatter system and is neglected in this discussion.

Continuous signals are considered to result from: (1) scatter from turbulent irregularities in D-region ionization, (2) partial reflections from ionization gradients, and (3) overlapping reflections from the ionized trails of many small meteors. The sun causes ionization in the D and E regions by photo-ionization, soft X-rays, and bombardment by high-energy particles. Therefore, the ionization is affected by solar flares, sunspots, and ionospheric storms. A plot of the electron densities (the ionization) up to 500 km above the earth's surface is shown in Figure 5.

The strength of the received signal depends on the type of antenna, the orientation, the geographic position, and the time of day and year. Typical variations recorded are a 10-db diurnal variation and a 10-db winter-summer variation in signal intensity for a link between Anchorage and Barrow (Alaska); a 10-db winter-summer variation was also recorded for a link between Cedar Rapids, Iowa, and Sterling, Virginia [38]. The day-to-day variations in propagation loss with ionospheric scatter are greater in the Arctic than in the temperate latitudes. Figure 11 shows the seasonal variations experienced in the latter region.

A diagram for a typical ionospheric scatter link is shown in Figure 12. The maximum distances for ionospheric scatter are determined by the single-hop distances from the scattering height — the signal levels are too low for further hops. The limits on the distances are: (1) the minimum range (about 1000 km between ground stations) is determined by the increased losses due to the increased scattering angle θ, and (2) the maximum range (about 2000 km) is determined by the earth's curvature.

Various formulas have been derived to express the path loss; in most of these the path loss is approximately dependent upon the inverse eighth power of the frequency of the transmitted wave and the inverse seventh power of the sine of one half of the scatter angle θ [43]. In
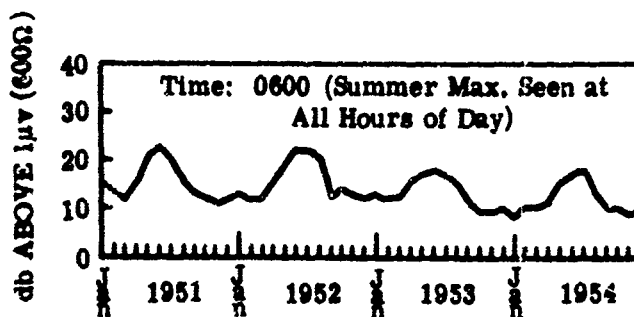

FIGURE 11. SEASONAL VARIATION [44]: CEDAR RAPIDS—STERLING.
f = 49.8 Mc, d = 1243 km.

46
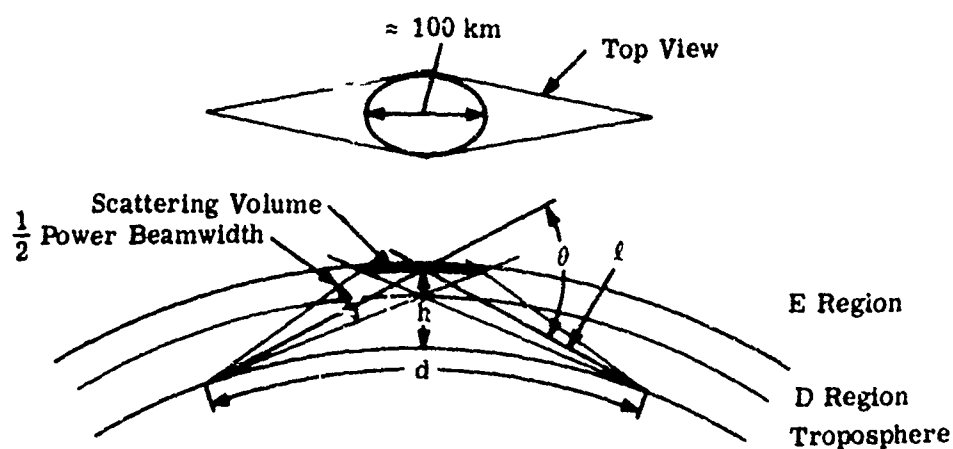
FIGURE 12. GEOMETRY OF IONOSPHERIC SCATTER PROPAGATION [44].
θ = scattering angle in degrees, l = ray distance, h = altitude of scattering stratum = 85 km (can range from 60 to 100 km). d = distance on earth: mean radius R = 3963 miles or 6378 km. (4/3 R is not used because tropo refraction takes place during a small part of the path length.)

general, a 1300-mile path loss is about 80 db greater than free-space attenuation at 30 Mc and about 90 db greater than free-space attenuation at 50 Mc.

Figure 13 shows idealized curves of path losses with distance for several different modes of propagation. Actual measurements of signals on an aircraft receiver are shown in Figure 14. These measurements were taken on a ground-to-air link with an aircraft flying at 35,000 feet.

FIGURE 13. IDEALIZED CURVE OF PATH LOSS WITH DISTANCE [10]

47

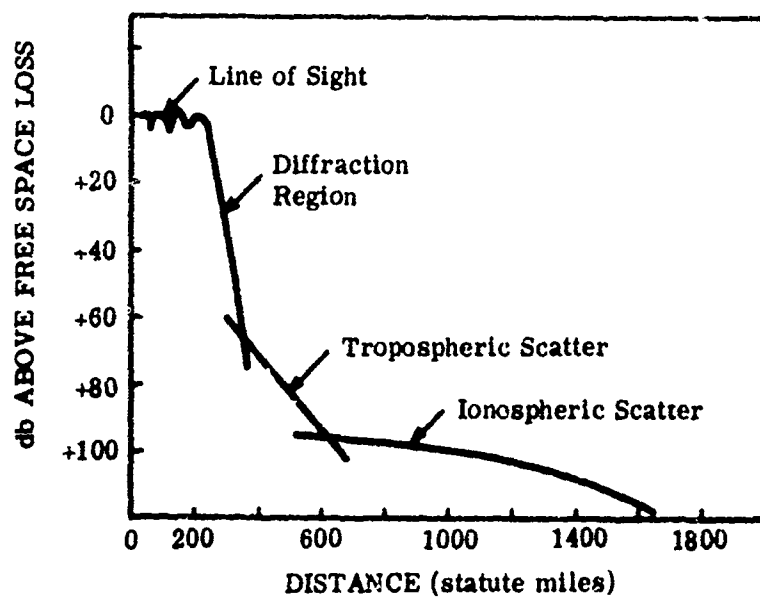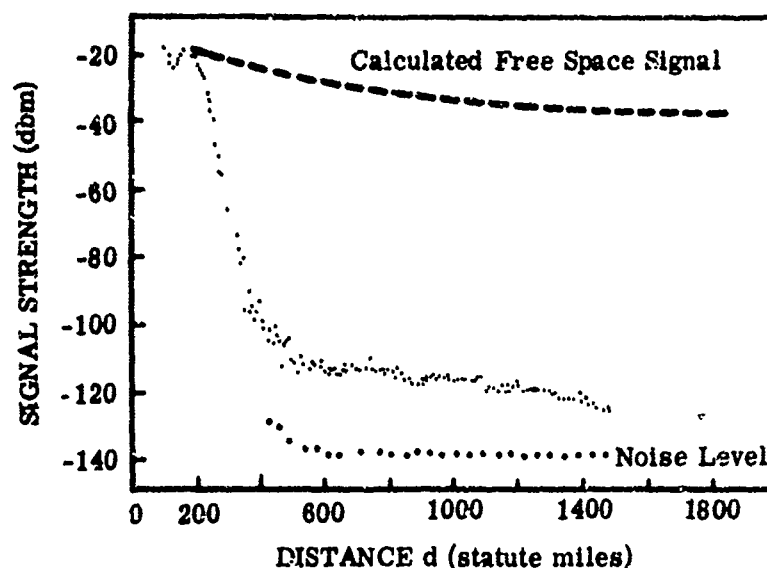FIGURE 14. SIGNAL STRENGTH DURING FLIGHT TEST OF 50-Mc COMMUNICA-
TION SYSTEM (GROUND-TO-AIR) [10]. 27 March 1961, 1-minute median levels.

Both galactic and atmospheric noise decrease with frequency. The transmission losses and
the resulting received S/N are dependent upon the frequency, with the most useful range from 30
to 60 Mc. At 50 Mc, approximately 5 kw are required with the use of a 60-wpm teleprinter chan-
nel (without error correction) for a typical system (over land) for satisfactory service 99% of
the time [38]. Scatter circuits have been used for multichannel teleprinter service and single-
channel voice service.

Multipath effects and doppler shifts limit the usable bandwidth. Multipath delays of 2 to
4 msec have been observed from off-path reflections caused by meteoric ionization. With antenna
beamwidths of 6°, digital transmission speeds are limited to about 500 bits/sec under worst con-
ditions. The maximum theoretical expected doppler shifts from meteoric "whistles" is about 6 kc
at 50 Mc. This results from the mixing of the continuous background signal with the meteoric
signal as the trail is formed. The short-term fading on the circuit follows a Rayleigh distri-
bution. When aircraft are considered, multipath becomes more of a problem since typical antenna
beamwidths are wide.

One of the advantages of ionospheric scatter in the auroral regions is that this mode of
propagation makes use of the upper D layer. Some work has been done to determine whether a re-
liable long-distance air-ground radio teletype (RTTY) system could operate across the auroral
belt [15]. A ground station was located near Bedford, Massachusetts, and an Air Force KC-135
jet tanker was equipped and flown as far north as Frobisher Bay (68° W, 64° N). Figure 14 shows
the signal strength recorded during a flight; the different modes of propagation can readily be
seen. Several findings in these tests are of interest. Auroral displays actually enhanced the
ionospheric signal. Magnetic disturbances reduced the noise level, probably by absorbing cosmic

48

noise. It was concluded that a successful air-to-ground, 60-wpm, RTTY channel could be operated to a range of 1100 miles with presently available equipment. However, static discharge noise at the aircraft was a problem. The noise on the wing-tip antennas, when the aircraft was cruising below the tropopause, was about 35 to 40 db above the noise on the nose and tail antennas. Attempts to reduce the static discharge noise with tape, static discharge wicks, and pre-RF amplifier filtering still resulted in about 8 to 10 db of noise above the normal expected background noise.

Ionospheric scatter methods proved to be more reliable than HF service for long-range communications, but not as reliable as tropospheric scatter at shorter ranges. Ranges up to about 1500 miles are possible with low data rates. Links have been designed for RTTY equipment. The effect of atmospheric noise in the frequency region of operation is minor; the major noises are cosmic, man-made, and precipitative (static discharge). Both cosmic and atmospheric noise are greater at the lower frequencies. Multipath is the primary limitation on the usable bandwidth. The lower limit of usable frequencies is determined by the m.u.f. of the normal skywave transmission for the F_2 layer. The upper limit of usable frequencies is determined mainly by the increased attenuation at higher frequencies. Usable frequencies for ionospheric scatter propagation range from about 40 to 60 Mc. An advantage of ionospheric scatter propagation is that it can be used when HF skywave propagation is poor, since ionospheric signals around 50 Mc are often enhanced by the same disturbances which disrupt HF communications.

A.1.3.3. Meteoric Scatter. A special case of ionospheric scatter propagation is the use of signals scattered by ionized meteor-trail reflections. The earth's atmosphere is continually being bombarded by meteors, occasionally by intense showers. It is estimated that there are at least 10^{10} particles with a total mass of one ton (or more) entering the atmosphere each day [45]. The capacity of the communication system depends upon the geometry of the incoming particles and their paths relative to the stations. Meteors enter from all directions, but there is a concentration in the plane of the earth's orbit, the ecliptic. An observer is carried into this cloud of particles at 6:00 a.m. and away from it at 6:00 p.m.; therefore maximum meteor activity occurs at about 0600 local time, and minimum activity at 1800. The earth's tilt causes this rate to change from season to season.

Particles entering the region of the ionosphere at the 80- to 120-km range are heated by collision with air molecules. Evaporated meteor atoms colliding with air molecules produce free electrons, thus leaving ionized trails which constitute the useful propagation media [20]. Line densities of the ionized trails vary from 10^{10} to 10^{16} electrons per meter. These are often classified into the following two groups: (1) under-dense trails — charge densities below 10^{14} electrons per meter — and (2) over-dense trails — charge densities above 10^{14} electrons per meter [45].

The expected signal amplitudes and the forms vary according to the densities of the trails. Radio waves pass through the under-dense trails with little modification, the reflection is specular (incident and reflected waves make equal angles with the meteor trail). Figure 15 shows a typical signal from an under-dense trail as a function of time. For over-dense trails, all
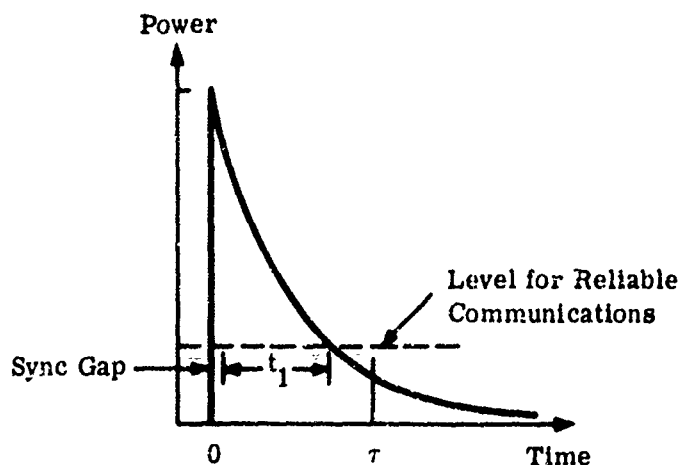
FIGURE 15. RECEIVED POWER FROM UNDERDENSE METEOR TRAILS [45].
Power reduced by $1/\epsilon^2$ in τ seconds. Transmit information during t_1.

the energy is reflected from a cylindrical surface about the axis of the meteor trail. The re-
flecting surface is at a radius determined by the electron volume density and the frequency.
The critical frequency, determined mainly by the electron density, is the same critical frequency
mentioned under ionospheric propagation by means of skywave. For frequencies above the critical
frequency, a portion of the RF wave penetrates the cylindrical surface. Figure 16 shows the re-
ceived power from over-dense meteor trails as a function of time.

The received power from the meteor scatter fluctuates diurnally and from day to day. There
is a definite limit to the advantage of high-gain antennas, especially if they are aimed along
the great-circle route between stations. From Figures 15 and 16 it is possible to define the
times that these signals remain above a threshold. This total time above the threshold by all
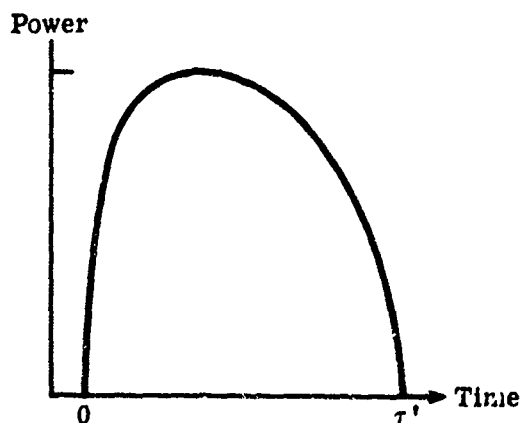

FIGURE 16. RECEIVED POWER FROM OVERDENSE TRAILS [45]

50

the signals depends more on than just the number of trails seen. The statistics of signals scattered from meteor trails depend on: (1) the position of the meteor in latitude and longitude, (2) the altitude (useful trails are formed in the 90- to 100-km altitude range), and (3) the ionization, which depends on the mass of particles and the altitude.

The assumption of specular scattering requires that half of the principal Fresnel zone must be formed within the length of the trails. This confines attention to certain parts of the sky and certain orientations of trails.

Figure 17 shows the effectiveness of regions of the sky rated in terms of communication capacity for a meteor communication system. These results take into account all three items above. Lack of information on the incidence pattern of meteors made it necessary to assume their uniform distribution in order to construct a "contour" chart. As the diurnal maximum sweeps across the regions in question, the symmetry in Figure 17 is affected.

Factors determining the limitations on transmitting frequency are: (1) the losses from meteor scatter increase as the cube of the frequency, thus setting an upper limit of about 50 Mc, and (2) the presence of competing modes of propagation, which can cause severe fading and multipath problems, set a lower limit of about 30 Mc.

The nature of meteoric-scatter propagation makes burst-type communication necessary. In such an intermittent system, the bandwidth can be increased without increasing the error rate,
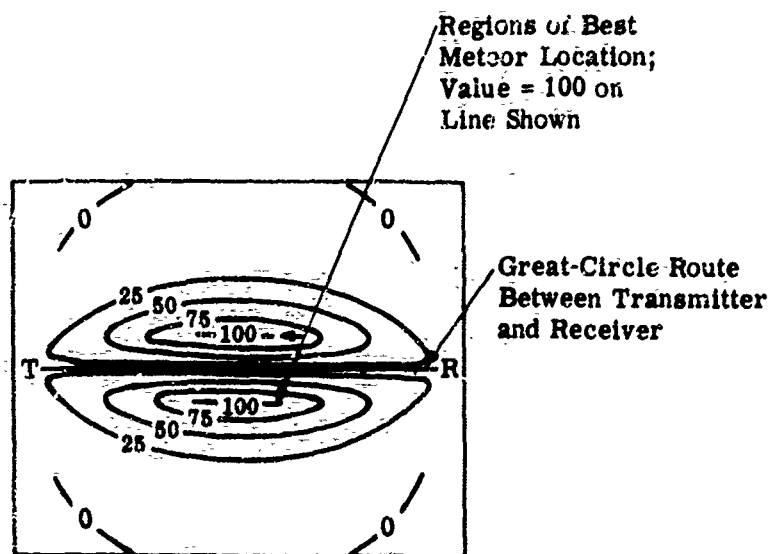

FIGURE 17. EFFECTIVE AIMING REGIONS FOR A METEOR COMMUNICATIONS SYSTEM [45]. Contours incorporate both numbers and durations of signals. Contours are shown on ground but trails are formed at altitudes of 90 to 100 km. Regions rated according to communication capacity. As shown, the antennas should not be aimed along the great-circle route between stations.

if the signal level required for data transmission is raised. This, of course, reduces the duty cycle. Thus, in designing this type of system, it must be decided whether to use a high rate a small part of the time or a low rate a large part of the time. Some actual choices for a duty cycle are discussed later in the section.

Several meteor-scatter systems have been operated. Some specifications for experimental systems are given here to indicate the equipment required for this type of operation.

The U. S. Naval Electronics Laboratory (NEL) operated a meteor scatter link from a fixed station near San Diego to a mobile unit near Eureka, California [46]. The signals were transmitted at 40.14 Mc and 42.10 Mc with a power of 1.5 kw over a distance of 680 miles. The average data rate varied from 14 to 22 wpm with a burst rate of _100 wpm. The transmissions totaled 3000 words in three hours, both ways, with an error rate of about 1.3% at the master station.

Jansky and Bailey, in cooperation with the Advanced Electronic Center of General Electric, established an experimental meteor scatter link between Washington, D. C., and Ithaca, New York, in 1960 [47]. The link operated at 48.82 Mc with a power of 250 watts over a distance of 250 miles; duty cycle for this system was 1% with a bit rate of 625 bits/sec. The distribution of meteor burst signal duration recorded over this link is shown in Figure 18.

In 1956 the Canadian Defence Research Board sponsored the JANET system [45]. One of these meteor scatter links operated with a power of 500 watts over a distance of 560 miles between Port Arthur, Ontario, and Bolton (near Toronto). The most important requirement in the design of the JANET system was to supply a gating mechanism to: (1) provide as short a delay as possible between detecting a trail and starting information transmission, and (2) to turn off the transmission before the signal dropped below the necessary S/N level. The system was designed to operate with fading rates as great as 60 db/sec. Two-way communications were necessary in JANET. Both stations measured the received S/N; gating was controlled by the S/N at the opposite end of the link. Separation of the transmitter and the receiver at one end of the link is limited by reflection, which introduces the danger of intermodulation. If the sun gets in the beam, the noise increases by about 6 db at 40 Mc.

The "gate-on" time during the 1956 tests averaged about 180 seconds per hour, giving a duty ratio of 5%; during this time the sync data and the information were sent over the link. The information rate on the average was 34 wpm, ranging from 1 to 60 wpm, with the error rate ranging from 0.1% to 4% (modal value of 1%). During a later test in January 1957, the error rate was reduced to 0.09% and the average information rate was increased to 60 wpm.

From both the experimental results and the theory it is evident that meteor scatter can be used in a communication link. Reflections usually take place in the 90- to 100-km height range over frequencies of 30 to 90 Mc. Most links to date use a frequency of about 50 Mc. Signals from meteor-trail scatter are stronger than from other types of scatter. However, the higher signal strengths are intermittent, making burst communication necessary. Duty cycles as low as 1% are used, and the equipment becomes complicated because of the storage and interrogation requirements. Furthermore, the link must be tested continually to determine when it exists. Ranges up to 1200 miles are feasible.
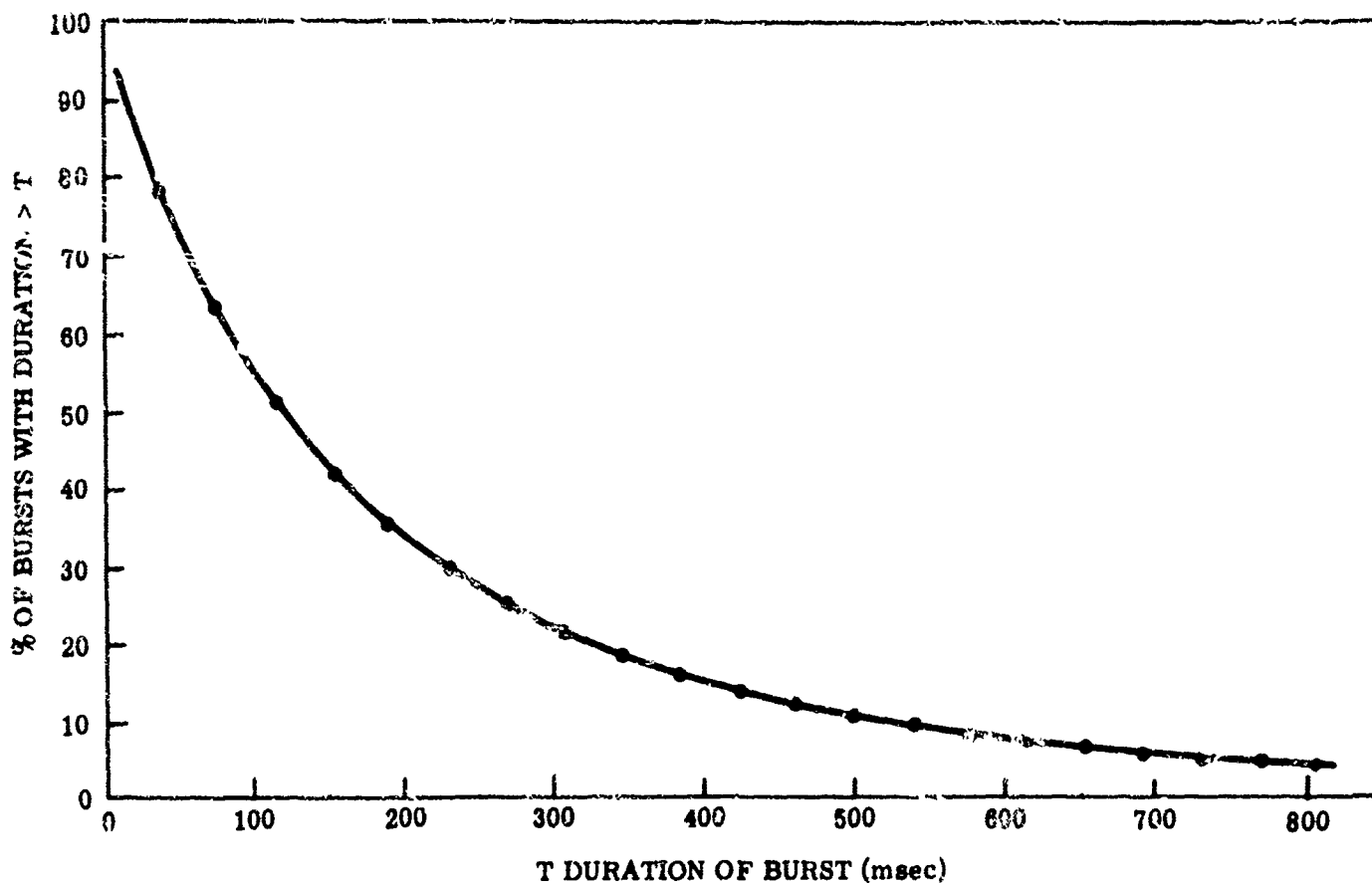
FIGURE 18. METEOR-BURST DURATION DISTRIBUTION [47]. Washington. D. C.
to Ithaca, N. Y . March 1960, f = 46.82 Mc. P_t = 250 watts. BW = 6 kcs.

In summary, specific advantages of this mode of propagation are: (1) it uses a spectral region not normally used for long-distance communications, (2) it is free from blackout due to ionospheric fluctuations, (3) it is capable of handling high, instantaneous, data rates (2400 wpm), although the average data rates are low (60 wpm has been achieved), (4) it makes low transmitter power feasible because of the low losses, and (5) there are few restrictions on modulation as compared to continuous-transmission scatter systems. (The "doppler-whistle" — which results from the meteor signal's mixing with a continuous background signal as the meteor trail is formed — still occurs, but only for the first few msec, during the time normally used for initiation purposes.) The significant disadvantage of this mode is that its intermittent nature makes complex equipment necessary.

A.1.4. LINE OF SIGHT. In general, the characteristics of line-of-sight transmission between terrestrial stations are well known. The addition of relays to extend the range beyond the radio horizon introduces practical problems, such as the number and placement of relay stations, to provide the desired coverage. (These problems, as they apply to North Atlantic communications, were discussed in Section 4.1.6.)

53

When satellite relays are considered, additional problems arise because of the long paths which must penetrate the troposphere and ionosphere.

A.1.4.1. Terrestrial Relays. Two cases of interest are transmission between one elevated and on ground-level terminal, and transmission between two elevated terminals.

If appropriate constants and assumptions are introduced into the equations for line-of-sight ranges, the following widely used approximations are obtained for a smooth spherical earth of 4/3 the true earth's radius.

$$d = \sqrt{2h} \qquad \text{ground level to elevated terminal} \qquad (2)$$

$$d = 2\sqrt{2h} \qquad \text{grazing path between two elevated terminals} \qquad (3)$$
$$\text{at the same elevation}$$

where d = range (miles)

      h = terminal elevation (feet)

Figure 19 presents these values for elevations appropriate to aircraft terminals.

One aspect of over-water communication which is often troublesome for horizontally polarized HF and for all polarizations for higher frequencies is reflection from the water. The interference resulting from the simultaneous arrival of the direct wave and the reflected waves produces fading having a period which is a function of the time rate of closure between the ends of the circuit, the distance (in wavelengths) between the ends, and the heights (in wavelengths) of the ends above the plane of reflection. The amplitude excursion of the signal is a function of the coefficient of reflection of the reflecting (earth or water) surface, and the relative gains of the antennas in the direction of the direct paths with respect to the gains in the direction of the reflected paths.

When one end of the link is a fixed antenna (ground station) the phenomenon may be visualized as a ground antenna pattern which is lobed in the vertical cross-section. Over water or good, smooth earth, the lobe structure can be deeply cut and well defined. A mobile station passing through this structure may experience "blackouts" over large areas, the extent and location of which are a function of altitude, frequency, and height of the ground station antenna. When the antenna is over an "earth" which is "rough" or irregular (irregularities which are large compared to a wavelength), the lobe structure is irregular, less deeply cut and with less likelihood of extensive low signal areas. Statistical treatment is the only satisfactory quantitative approach to the analysis of this latter condition. In any event, the number of lobes and "nulls" increases with the height of the antenna above the "ground." At VHF, cities, rugged hills or mountains in the reflection zone produce an apparently random lobing. It is practicable to predict the lobe structure only in a statistical sense. Oceans, lakes, and pastoral plains produce a relatively well defined and predictable lobing.

Placement of a fixed antenna at a small fraction of a wavelength above ground (when horizontally polarized) or directly upon the ground (when vertically polarized) will eliminate the

54

DISTANCE, d (miles) — vertical axis

$d = 2\sqrt{2h}$
Two Elevated Terminals, Grazing Path

$d = \sqrt{2h}$
One Ground and One Elevated Terminal
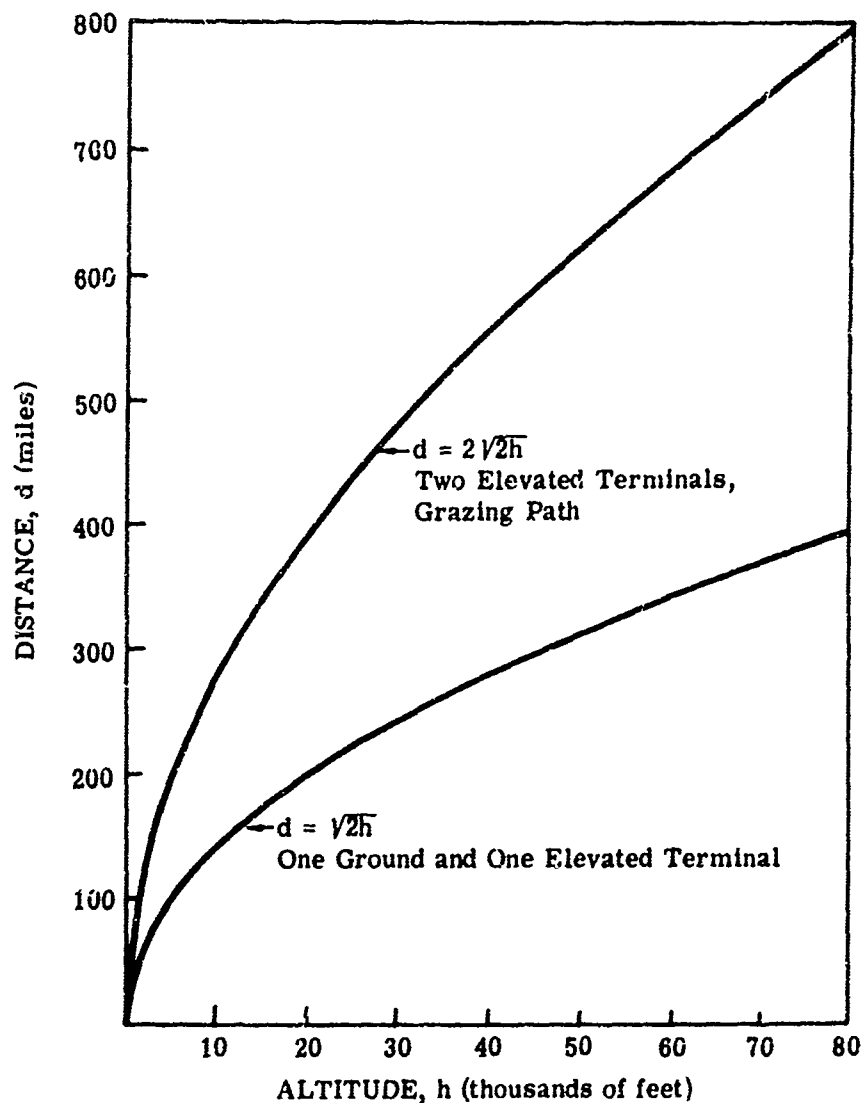
ALTITUDE, h (thousands of feet)

FIGURE 19. LINE-OF-SIGHT RANGE: FOUR-THIRDS EARTH ASSUMED

lobing (and consequent fading when the other end of the link is mobile). However, at VHF and above this is not generally a practicable solution since the increase in line-of-sight distance with antenna height must be sacrificed.

For both the air-to-air and air-to-ground cases, controlling the vertical directivity of the antenna patterns to minimize the illumination of the ground plane reflection zone will provide some relief. However, the effectiveness of this measure is sharply limited by the difficulty of controlling the directivity of practical airborne antennas, the necessity for airborne antenna response for all pitch and roll angles and by the necessity for illumination by the ground antenna of elevations down to the horizon.

55

A.1.4.2. **Extra-Terrestrial Relays.** The two primary problems in relays to satellites or other extra-terrestrial bodies (e.g., the moon) and (1) the large attenuations produced by very long paths, and (2) the noise background are discussed in some detail in Appendixes A.1.5 and B.1.3.

In addition to these "normal" propagation factors, there are anomalous conditions arising from a disturbed ionosphere. At frequencies above 1000 Mc, ionospheric disturbances can be neglected. However, when extreme concentrations of free electrons are present in the ionosphere, RF propagation through the ionosphere at VHF and even UHF may be subject to absorption, reflection, and scintillation.

Before arriving at the recommendation contained herein, that an ATC satellite system should operate in the 118- to 136-Mc VHF region, it was necessary to verify the assumption that reliable operation in this band was possible despite auroral disturbances.

Compilations of experimental data and theoretical predictions [48] indicate that at 136 Mc attenuations greater than 0.4 db should occur less than 0.2% of the time, even in the auroral zones. However, a report from the U. S. Army Signal Research and Development Laboratory [49] stated that during the auroral disturbances of November 1960 there was a complete loss of VHF frequencies (up to 216 Mc) being monitored from the Transit 2A satellite.[14] In December 1961, a similar loss of signals at 144 Mc from Oscar I was reported by an observer in the auroral zone, though the conditions of the observation were less precisely specified than those reported by USASRDL [50].

Conversations with personnel at Bell Laboratories, NASA Headquarters, Hughes Aircraft, Rand, Stanford Research Institute, and the Transit Project Office, indicated that they had encountered no loss of VHF satellite signals directly attributable to auroral conditions — nor were they aware of anyone else who had encountered such a loss. NASA personnel stated that Courier 1B and Vanguard I operated during the period in question in the 109-Mc range with no known losses of signal. The Transit group pointed out that low power supplies and poor orientation of the satellite account for many reported failures of satellite signals. It is our present opinion that the available information justifies the use of VHF frequencies for ATC satellite communications.

A more precise understanding of the causes, intensity, and frequency of occurrence of VHF fading would be desirable. The rarity of significant disturbances, however, would require a program of several years duration to obtain statistically useful information. Since most satellite telemetry has been conducted at VHF, it may be possible, through a detailed analysis of existing

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[14]The auroral disturbances which occurred at that time had a severity of magnitude 3+. The Radio Astronomy Group of the Electrical Engineering Department of The University of Michigan indicates that during periods of mild sunspot activity, auroral disturbances as great as magnitude 3 occur approximately twice a year, and as often as twelve times a year during periods of extreme solar activity. Since magnitude 3 on the disturbance scale was intended to indicate maximum severity, the 3+ designation exceeds any anticipated condition and is therefore assumed to occur rarely.

records, to obtain useful information. The many unknown and uncontrolled factors in such data might be resolved if reports from enough satellite and different observation points were carefully correlated. Periods known to have been disturbed could be examined in detail. Again, this represents a program of considerable magnitude.

A.1.5. NOISE-FREQUENCY CONSIDERATIONS. A consideration of operating frequencies is not complete without a knowledge of the expected noise. This section briefly discusses the noise factors applicable to an aircraft communications link. There are several facts which require special attention in an aircraft environment.

(a) Since signal levels are typically low, the attenuations at HF (caused by non-deviative absorption) and at SHF (caused by heavy rainfall) may become important.

(b) Aircraft and satellite RF equipment will probably be designed with vacuum tubes and transistors. The very low noise RF amplifiers (such as masers) do not seem practical at present or in the near future.

(c) Since typical aircraft antennas usually have wide beams there is a possibility that the sun may be included in the antenna beam. Figure 20 illustrates the variation of effective noise temperature when the sun is viewed with directive antennas.

The available data [8, 51-54] on noise within the range of interest are plotted in Figure 21, and the pertinent attenuations are shown in Figure 22. On plots of this type it is impossible to show all of the different variations; thus, as far as possible, fairly representative limits are shown. The curves for cosmic noise assume a pencil beam; the attenuation caused by heavy rainfall is about the maximum that can be expected. Although the ionospheric attenuation is shown for a disturbed condition known as Polar Cap Absorption (PCA), later stages of the storm increase the attenuations at the lower latitudes. Most of the available results apply to the PCA stage; therefore these are the results shown. The peculiar shape of the noise curves of the sun results mainly from the frequency dependency of the effective diameter of the sun. Within these restrictions, the results are fairly self explanatory. Notice that the S/N is degraded by two contributing factors: (1) the active sources of noise (such as cosmic noise), shown in Figure 22, and (2) the signal attenuators (such as heavy rainfall or oxygen), shown in Figure 21.

To define an effective noise temperature for an attenuator is fairly common. However, this method has drawbacks when combined noise temperatures are desired. For this reason the curves for active sources and attenuators are kept separate in Figures 21 and 22.

In order to discuss optimum operating frequencies, some choices must be made about a particular application. For a situation representative of the aircraft-satellite problem, curves are shown in Figure 23 for the following two sets of conditions:

(a) "maximum expected noise" — a combination of the maximum values for cosmic noise, vertical antenna ($\gamma = 90°$), a constant antenna beamwidth ($\overline{\gamma}$) of 50°, presently available triode receiver front-end stage using a 417A up to 200 Mc, crystal
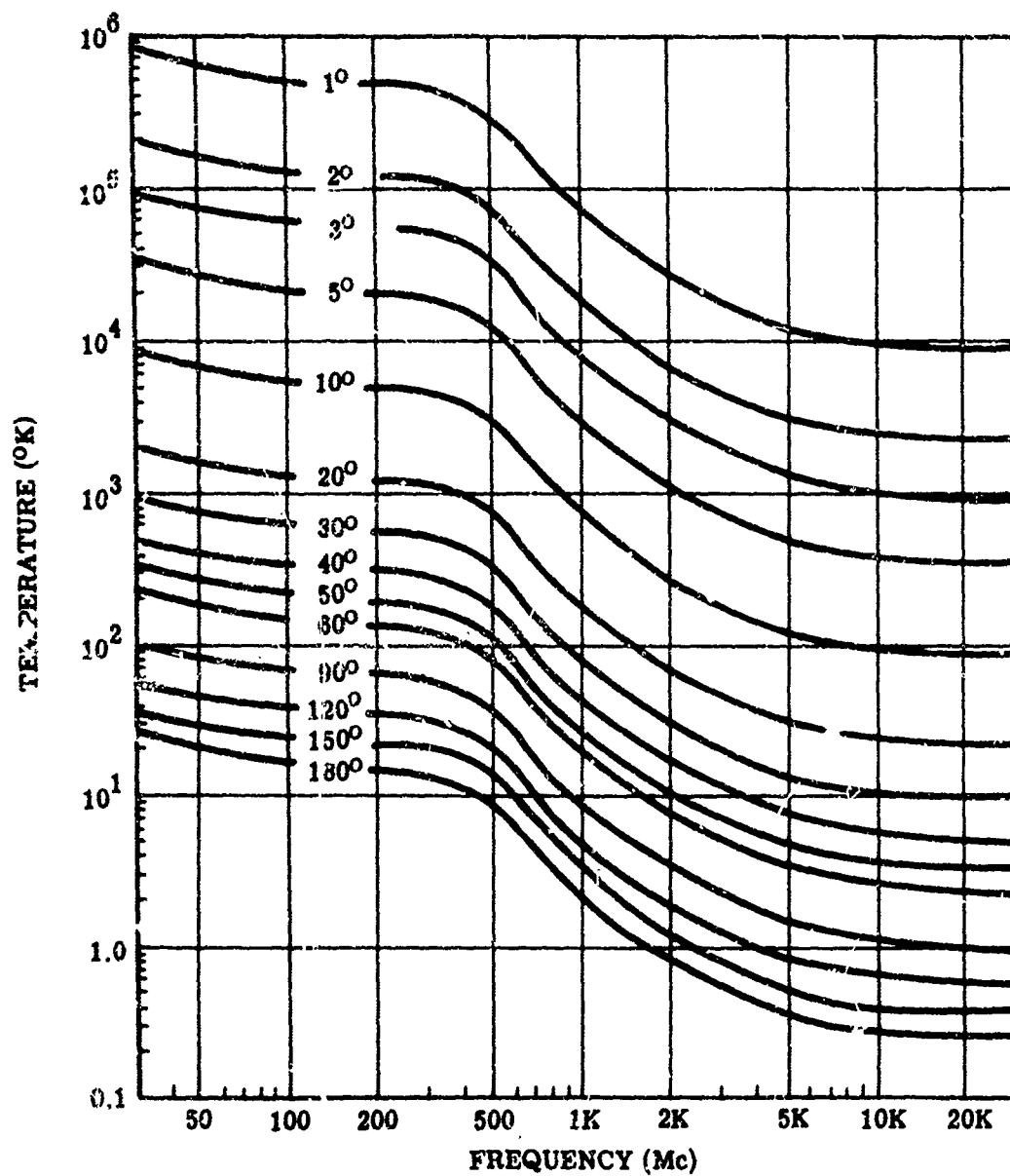
FIGURE 20. EFFECTIVE NOISE TEMPERATURE OF THE SUN. (It is assumed that the sun is viewed by a sharply defined conical antenna beam whose beamwidth is indicated on the curves.)
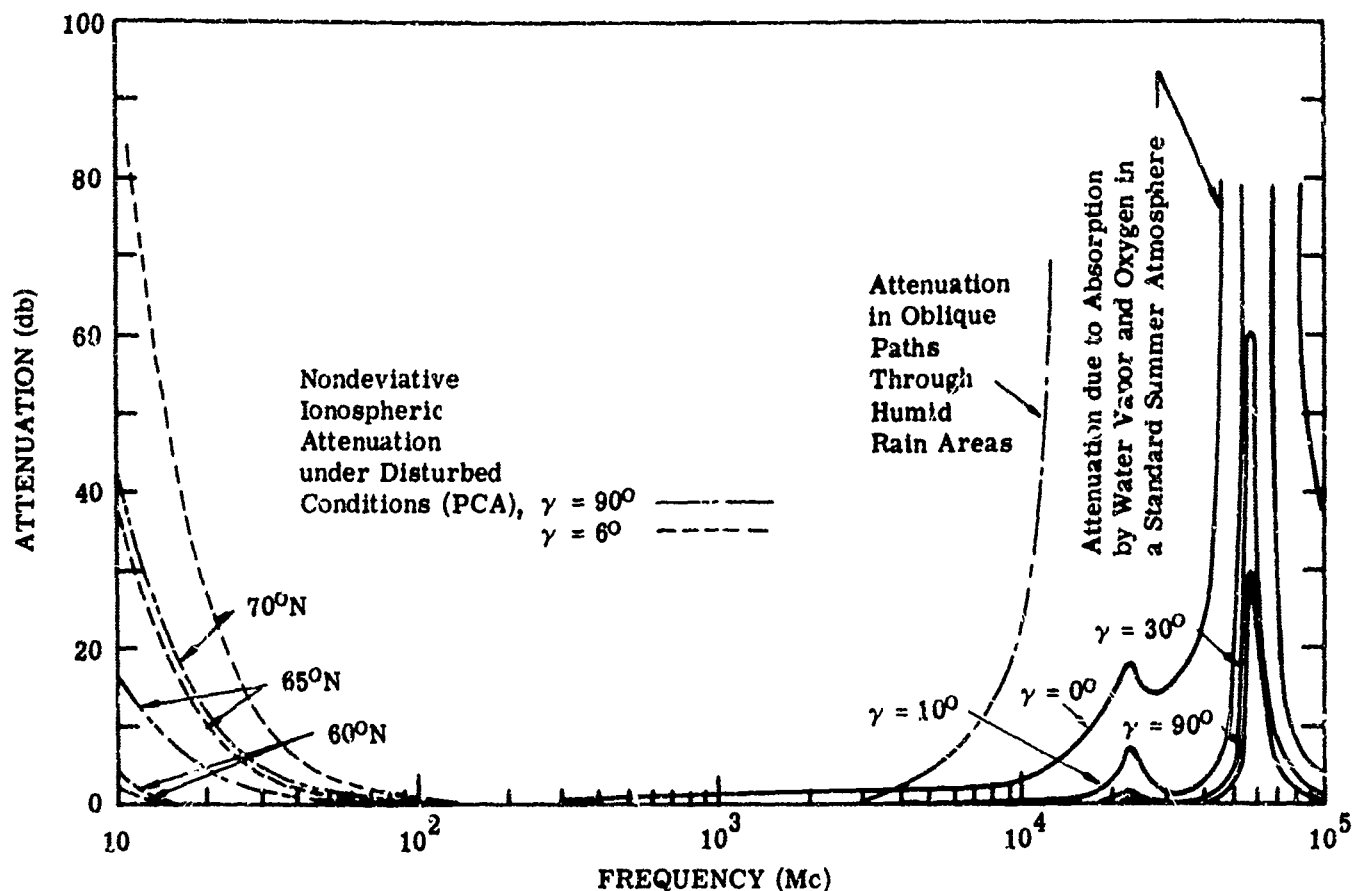
FIGURE 21. ATMOSPHERIC ATTENUATIONS INVOLVED IN AIRCRAFT COMMU-
NICATIONS. Antenna inclinations = γ, nondeviative ionospheric attenuation assumes
single penetration of the D layer.

mixer at higher frequencies, daytime operation (sun included within the beam-
width), heavy rainfall, and disturbed ionospheric conditions.

(b) "minimum expected noise" — a combination of the minimum values for cosmic noise,
vertical antenna ($\gamma = 90°$), constant antenna beamwidth (ψ) of $50°$, presently
available triode receiver front-end stage using a 216B up to 600-Mc crystal
mixer at higher frequencies, daytime operation (sun included within the beam-
width), no rain and a summer atmosphere assumed, and disturbed ionospheric con-
ditions.

Such effects as antenna side lobes, which "spill-over" and look at the earth, and trans-
mission losses between antenna and receiver are omitted here because of their low sensitivities
to operating frequencies. Although precipitation noise in the aircraft is frequency sensitive,
the effects of this type of noise are so dependent upon the methods of suppression (if any) that
they have been neglected. A discussion of precipitation noise and methods of suppression can
be found in Reference 55.
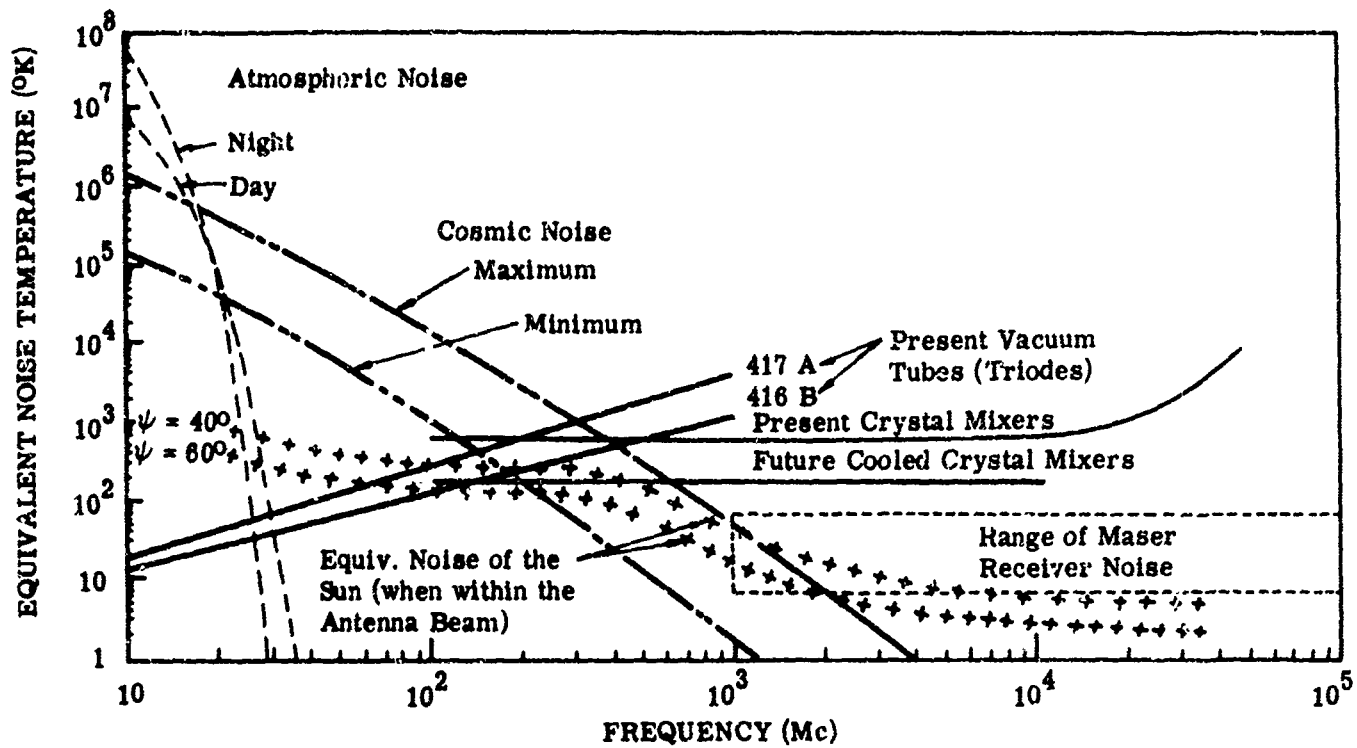
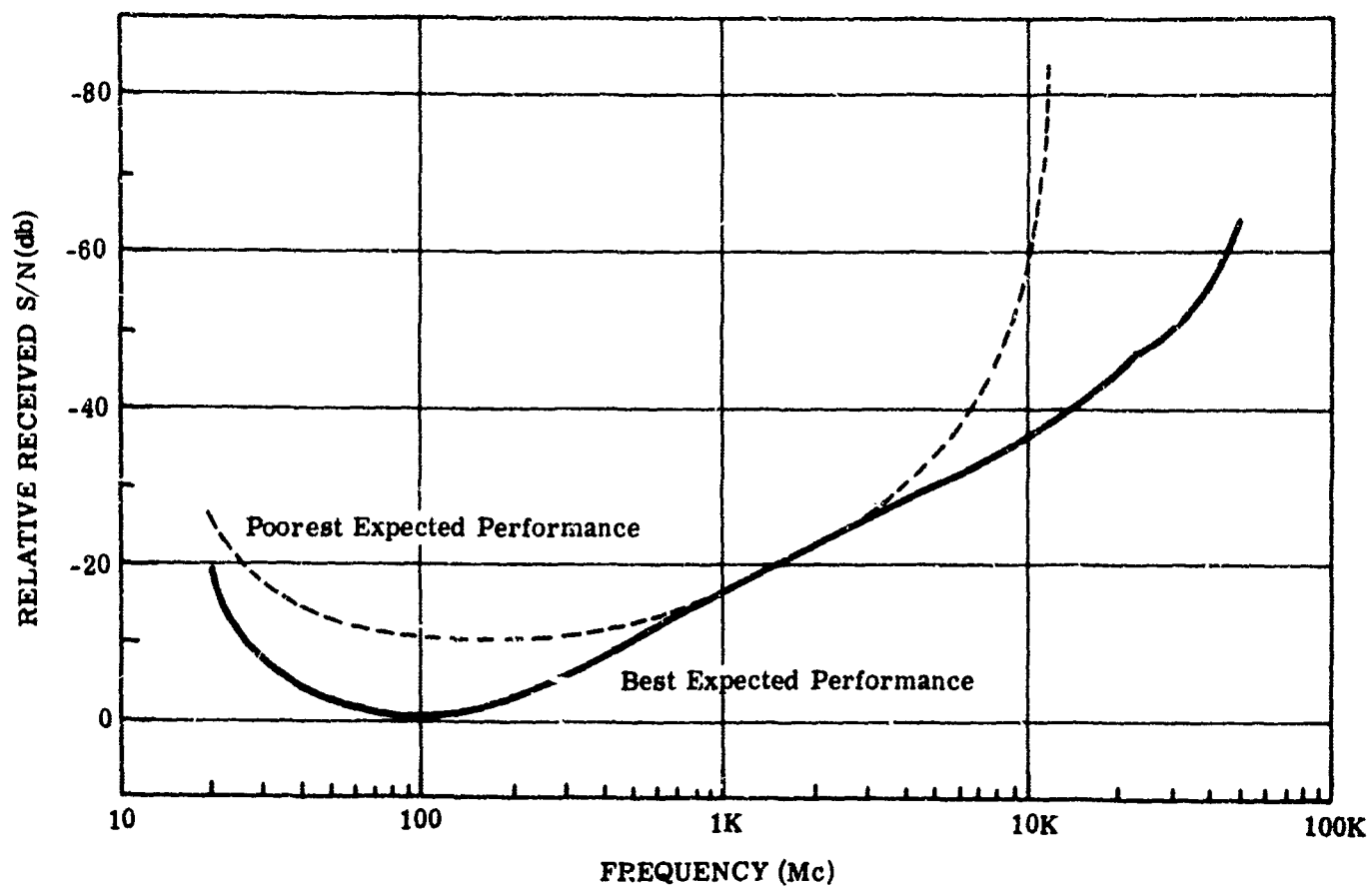FIGURE 22. NOISE FACTORS INVOLVED IN AIRCRAFT COMMUNICATIONS.
Antenna beamwidth = ♥.

FIGURE 23. RELATIVE RECEIVED S/N RELATIONS AS A FUNCTION OF FRE-
QUENCY. Constant RF bandwidth, transmitter, power, range, and unity gain
antennas.

61

Appendix B
SATELLITE STUDY

B.1. SYSTEM DESCRIPTION

A satellite radio-relay system will provide highly reliable over-ocean ATC communications. Because of the difficulty and the long delays in acquiring radio-spectrum channel assignments, special consideration has been given to the use of frequencies which are believed to be readily available: 118-136 Mc, 1540-1660 Mc, and 5000-5250 Mc [5]. Since the airline industry has an estimated investment of 500 million dollars in VHF radio equipment, it is especially important to examine the use of VHF in a satellite system.

Because of the complexities involved in determining the price to be charged against a civilian project for boosters which are essentially military rockets, and because of the constant improvements in satellite launch vehicles, it has not been possible to obtain extensive data with which to verify certain costs. Although the production costs of existing launch vehicles are fairly well known, the probablity of successfully injecting a communications package into orbit cannot be firmly established. Thus the satellite cost data discussed herein may be somewhat pessimistic, but it is hoped that the conservative estimates will prevent faulty conclusions.

It should be noted that this system has been postulated for purposes of discussion, and although it is considered readily achievable in both satellite and communication technology, it should not be considered optimum.

B.1.1. ORBIT SELECTION. Selecting a particular satellite communication relay system depends upon the orbit to be used. The selection of an orbit influences initial and operating costs, reliability or expected life, launch-vehicle choice, and availability of an operating system — factors which are interdependent in a nonlinear way. The problem of designing an optimum satellite communications system is in many ways analogous to maintaining an old inner tube: each time one weak point is reinforced, some other weakness develops.

Two basic orbits merit serious consideration: the medium-altitude, approximately circular, inclined orbit; and the "stationary" or 24-hour, circular equatorial orbit. A number of other possible orbits were discarded in preliminary examinations because of apparent technical or cost disadvantages. Several of these are discussed briefly at the end of this section; also discussed is the number of 24-hour satellites required to provide varying degrees of "world-wide" coverage.

Since the range component of the path attenuation varies as the square of the distance between two points, the attenuation at synchronous altitude is approximately 12 db greater than for the 6000-mile satellite (Figure 24). Figure 25 shows that the minimum beamwidth of an antenna looking at the earth and covering the North Atlantic area is about 10°; at 6000 miles altitude, the beamwidth must be opened to about 30°. Figure 26 shows that for typical high-gain antennas, these beamwidths correspond to about 25 db and 16 db, respectively. Thus the synchronous-satellite case is within 1 db of the medium-altitude case because of the higher usable antenna
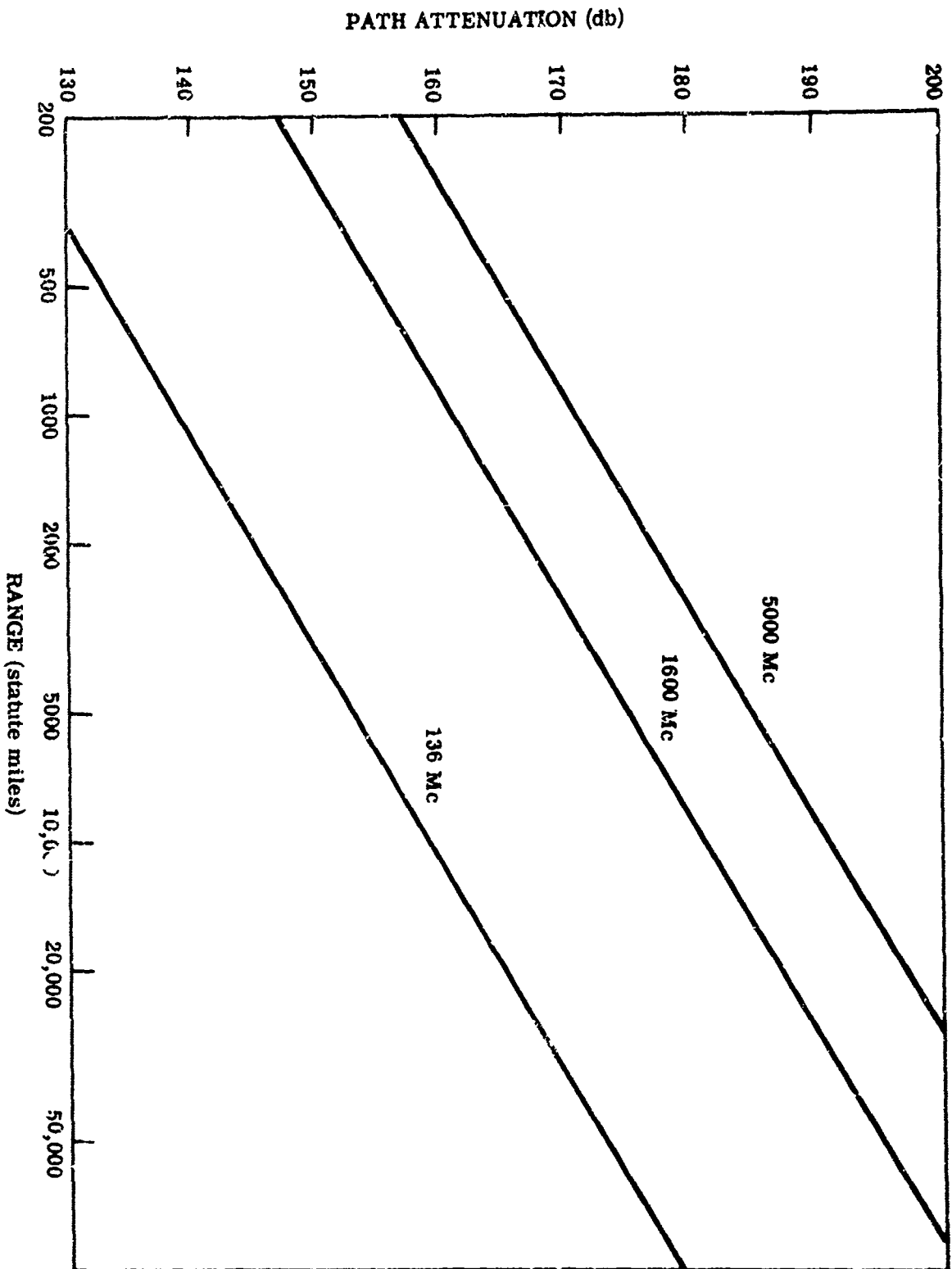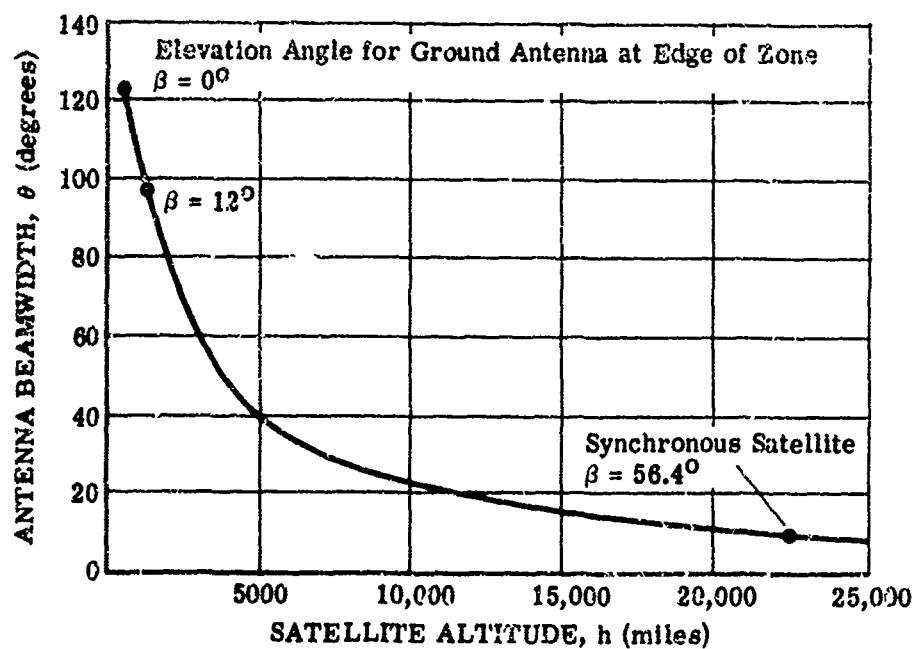
62

FIGURE 24. FREE-SPACE PATH ATTENUATION

FIGURE 25. SATELLITE ANTENNA BEAMWIDTH FOR COVERAGE OF THE NORTH ATLANTIC REGION. Region based upon a 4000-mile diameter circle centered at 37^OW, 43^ON; nominal coverage 30^ON to 70^ON and 0^OW to 75^OW.
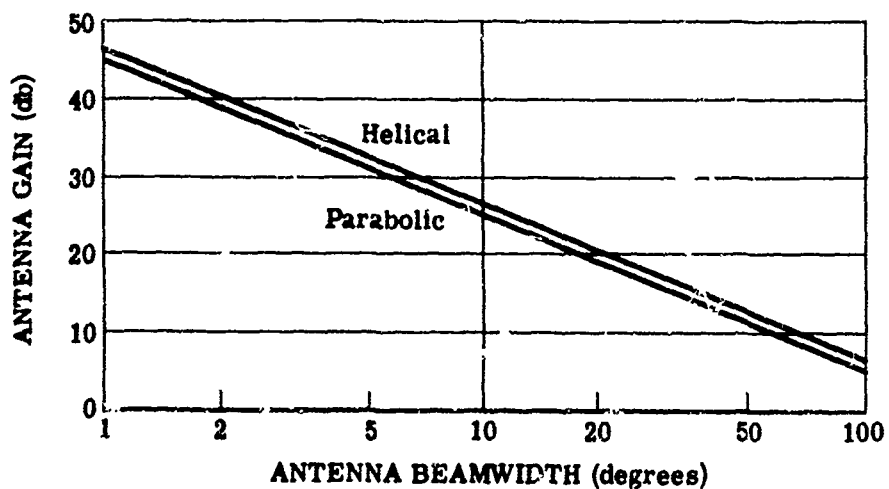

FIGURE 26. GAIN-BEAMWIDTH RELATIONS FOR HELICAL AND PARABOLIC ANTENNAS

64

gains. Further, the aircraft antenna for medium-altitude inclined orbits must provide horizon-to-horizon coverage, whereas the 24-hour, equatorial orbits permit limiting the aircraft antenna look angles to $12°-58°$ above the horizon. In terms of gain, the antenna for the medium-altitude case will have 2 db lower gain than the high-altitude case. Thus, the medium-altitude and synchronous cases have comparable effective propagation losses.[15] Hence, factors other than propagation will determine the choice of orbit height.

The destructive radiation effects of the Van Allen belts are more serious at the 6000-mile altitude (even though this is above the most severe levels of the inner Van Allen belt) than at synchronous altitude.

The ground station antennas for the medium-altitude orbits must be able to track the satellite positions; for synchronous orbits, they can be essentially fixed since drift of the stationary satellite will be quite small when active satellite position control is employed.

Bell Laboratories has stated that between 30 and 50 medium-altitude satellites are required for a commercial satellite communication system having a 99% probability that a satellite will be in mutual view of the ground terminals [56]. On an area basis this probability is necessarily lower.[16] Should multiple satellites be used for ground-to-aircraft relay service, some switching must be provided in both satellites and aircraft. That is, there must be some way for the aircraft to know which satellite is available for a relay, and the ground station must select the correct relay, depending on the aircraft and satellite positions — both of which are changing as a function of time.

Finally, the cost of a low-altitude system for five years is over 100 million dollars greater than that for a high-altitude system. Clearly, the serious economic disadvantages of the medium-altitude orbit dictate selecting the 24-hour orbit if technical feasibility can be established.

So far, only two types of orbit have been mentioned. Another type is the 24-hour circular orbit, with the orbital plane inclined with respect to the equatorial plane. It traces the fa-

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[15]All of the earth visible from a 24-hour satellite can be covered by opening the satellite antenna beam to $18°$ (20 db). Modifications of the aircraft antenna pattern would also be required for aircraft flying between $30°$ N and $30°$ S, since the satellite would be more nearly overhead. The resulting small propagation advantage of medium-altitude satellites would be more than outweighed by the greatly increased coverage available from a single synchronous satellite.

[16]One should be careful to note that the failure of a single 24-hour equatorial synchronous satellite will wipe out the entire communication system, but the loss of a single low-altitude satellite produces only a part-time failure. Thus, more than one high-altitude satellite will be required. (This problem is discussed in Appendix B.1.4.) Note, however, that the 99% probability that a medium-altitude satellite will be in view is a long-term average. There is a probability that is not negligible that outages of the order of 15 to 30 minutes may occur for an arbitrary ground station or aircraft position in the North Atlantic. The synchronous satellite provides coverage 100% of the time.

mi.'ar figure-eight pattern on the earth's surface. The top and bottom of the eight coincide
with the latitudes corresponding to the inclination angle, and the cross-over point of the eight
is a fixed point on the equato'. Three satellites would be required to cover the area in question.
Because this configuration requires ground stations with tracking antennas, and the satellites
themselves would be no simpler, the cost would be at least three times that of the single equa-
torial satellite. No significant technical advantage is gained by using the inclined orbit to
justify the additional cost since the primary objective is to provide communications for the
North Atlantic. However, installations designed to provide world-wide coverage could make ef-
fective use of an inclined orbit.

Lower-altitude, circular equatorial orbits (e.g., 6- and 12-hour periods) require more
satellites and provide no coverage at the northern extreme of the North Atlantic ATC regions.

Logically, once implemented for the North Atlantic, a satellite system would be extended
to provide world-wide coverage. Several orbit configurations were examined to determine the
number of satellites required to provide such coverage. The advantages of the 24-hour (synchronous)
orbit led to a decision to concentrate on 24-hour equatorial and inclined satellite orbits.
Manual methods used to evaluate coverage (i.e., plotting of coverage patterns on a globe and
transfer to maps) are laborious and time consuming. (The inclined orbits require plots at 1-
to 2-hour intervals to insure that the constantly changing overlap pattern maintains 100% cover-
age.) An extensive investigation would require a computer analysis.

The coverages obtained with various orbital configurations are briefly summarized below.

(a) Synchronous Equatorial-Orbit Satellites Only. Four synchronous satellites equally
    spaced around the equator would provide complete world coverage to 70° North and
    South for 5° minimum aircraft antenna angle above the horizon (see Figure 4).
    If the minimum antenna angle were 12°, complete coverage would be limited to
    64° North and South. Coverage of the polar areas could not be obtained with
    this configuration.

(b) Synchronous Inclined-Orbit Satellites Only. Five satellites in 45° inclined
    orbits, equally spaced around the equator and synchronized to cross the equator
    (northbound) with a 4.8-hour interval between successive satellites, would pro-
    vide complete coverage of the earth (5° minimum antenna elevation).

(c) Mixed Equatorial-Orbit and Inclined-Orbit Satellites. A minimum of three equa-
    torial and three inclined satellites, alternately spaced at 60° increments around
    the equator, would provide complete coverage of the world. The inclined orbits
    would be synchronized to cross the equator at 8-hour intervals (5° minimum antenna
    elevation).

B.1.2. COMMUNICATIONS CONFIGURATION. Once the orbit has been selected, the rest of the
satellite communication system can be postulated.

Figure 27 is a sketch of a possible relay system. The aircraft would use its VHF equip-
ment for data contact with the satellite, which would relay the data to the ground stations via

Land Lines

Ground Station

Ocean Cables

2-Simplex ATC Data
(Duplex Point-to-Point Voice)
Up: Command
Down: Telemeter

UHF
Channels

2-Simplex ATC Data
VHF Channel

Satellite
Relay

2-Simplex ATC Data
(Duplex Point-to-Point Voice)
Up: Command
Down: Telemeter

UHF
Channels

Ocean Cables

Ground Station

Land Lines

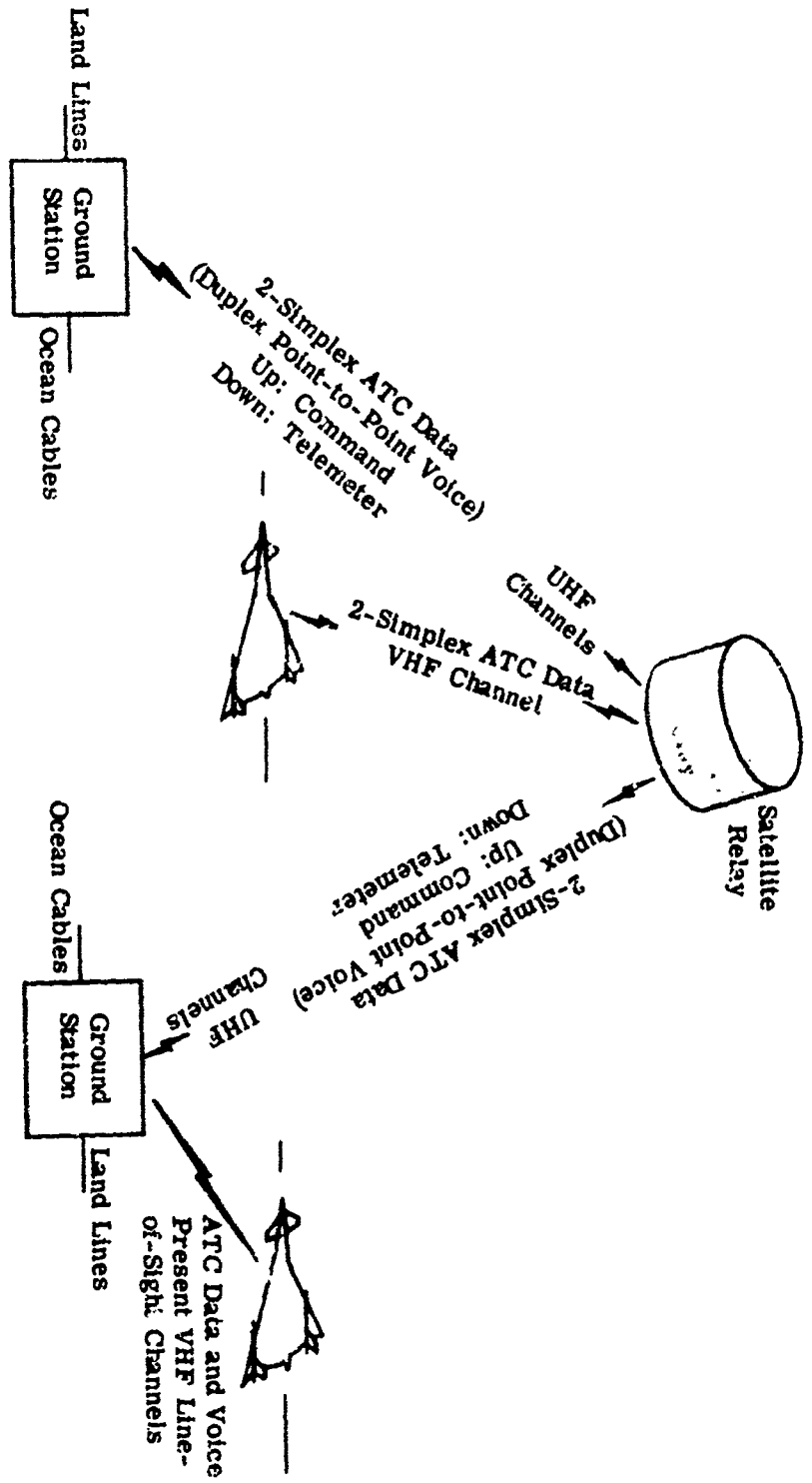ATC Data and Voice
Present VHF Line-
of-Sight Channels

FIGURE 27. POSSIBLE ATSAT CONFIGURATION

69

UHF channels. As each aircraft came within line-of-sight range of VHF ground stations, it would switch from satellite to ground-station frequencies.

The ATSAT system has the following capabilities. Two Simplex channels (transmit and receive on a push-to-transmit basis) from the ATSAT to aircraft in the North Atlantic control area are available. These channels are of data bandwidth only; either of them is expected to be adequate to serve the requirements for ATC information.[17] Having duplicate channel facilities available in the satellite improves the communications reliability of ATSAT. Also, one channel can be used for transmitting ATC data between the two ground stations if they are equipped with VHF transmitting and receiving antennas. This would reduce the cost of leasing commercial lines to connect the ground stations. If one channel should fail, there would still be sufficient capacity to meet ATC requirements. The traffic between ground terminals could be shifted to commercial facilities until a replacement satellite could be orbited.

The air traffic communication (ATCOM) channels from ground to satellite are in the UHF band between 1540 and 1660 Mc. The choice of specific frequencies in this band depends only on their availability, but assignments at the upper and lower ends of the band for isolation between transmitters and receivers in the multiplex antennas are desirable. The ATCOM channels from satellite to aircraft are in the VHF aeronautical band (118 to 136 Mc) so that radio equipment already installed in the commercial aircraft fleet can be used. Because the cosmic noise in the VHF band drops sharply as frequency increases, noise considerations would dictate operation at the high end of the band. However, since path losses increase as the square of frequency, the two effects tend to cancel each other under normal conditions. Figure 23 illustrates the results of combining the two effects. Abnormal conditions, such as auroral disturbances, which exhibit unusual concentrations of free electrons, can produce absorption and reflection phenomena which are less severe at the higher frequencies. However, the range of frequencies available in the 118 to 136 Mc band is not large enough to make the preference for high frequencies decisive.

The UHF telemeter and command channels shown between the ground and the satellite are required to control the communication channel from the ground and to provide certain information to the ground stations regarding the satellite's status.

Figure 28 shows the possible equipment configuration in the ATSAT. At the top of the diagram are the ATCOM frequency translators, which receive the UHF signals from the ground station and shift them to VHF for retransmission to the aircraft (or to another ground station, if the channel is being used for point-to-point communications). The UHF antenna for the frequency translator is multiplexed with the other UHF transmitters and receivers. Power isolation, which

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[17]The data requirements for ATC purposes have been determined for peak traffic loads expected in 1975. Section 3.2 contains an estimate of these data requirements, including the effects of synchronous orbit propagation delay times on the effective data rate. The data requirements for ATC purposes do not include those which may be needed for future navigation systems. If these requirements should be too large for inclusion with the ATC data, the duplicate channel could be used for this purpose.
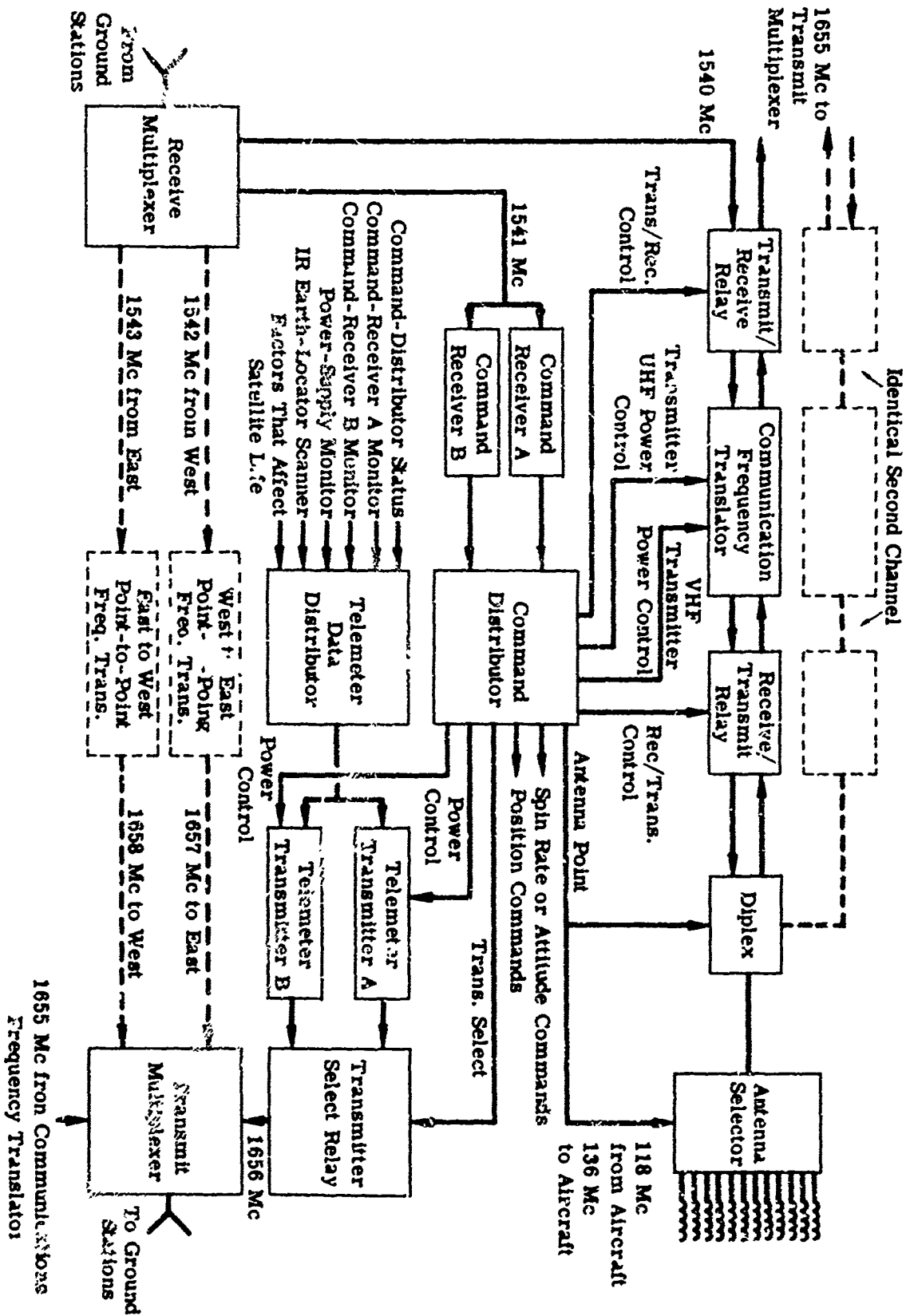
FIGURE 28. POSSIBLE SATELLITE-EQUIPMENT CONFIGURATION. For simplicity, identical second channel is not shown.

is obtained primarily in the diplexer, is aided by maintaining as wide a separation as possible between transmitting and receiving frequencies. The antenna for the VHF link to the aircraft is a 12-element helical antenna which must be deployed in orbit because of its size [57]. The individual helices have an antenna gain of approximately 16 db, which is required for adequate margins in the satellite-aircraft link. The satellite spin axis is parallel to that of the earth. One of the twelve elements will always point toward the earth. The element in use will be selected, either from the ground or by use of an infrared device in the satellite, used to detect the earth's edge and switch to the correct antenna. The use of a switched antenna is more of a concept than a firm recommendation. The firm requirements are 16 db of gain in a spin-stabilized vehicle and circular polarization. The phase dipole array proposed for Hughes Syncom II would be satisfactory except for lack of circular polarization and scaling difficulties encountered at VHF. The diplexer shown makes it possible for both of the communications packages to use the same antenna.

Below the communication frequency translators (Figure 28) are the command receivers and the command distributor; the receivers are paralleled so that either can be used to activate the command distributor.[18] The command distributor accepts instructions transmitted from the ground to the command receivers and sends them to the appropriate places. One example would be the command to control spin rate and attitude of the satellite.

The telemetry transmitters, also duplicated for reliability, appear below the receivers and the distributor. Information required by ground stations (e.g.; What is the status of the command distributor?) is transmitted from the satellite via the telemetry link. The answer to the question above would give some indication that the command receivers and distributor were operating properly. Data on the puncturing of satellite containers by micrometeorites could be transmitted to help predict the life expectancy of the satellite.
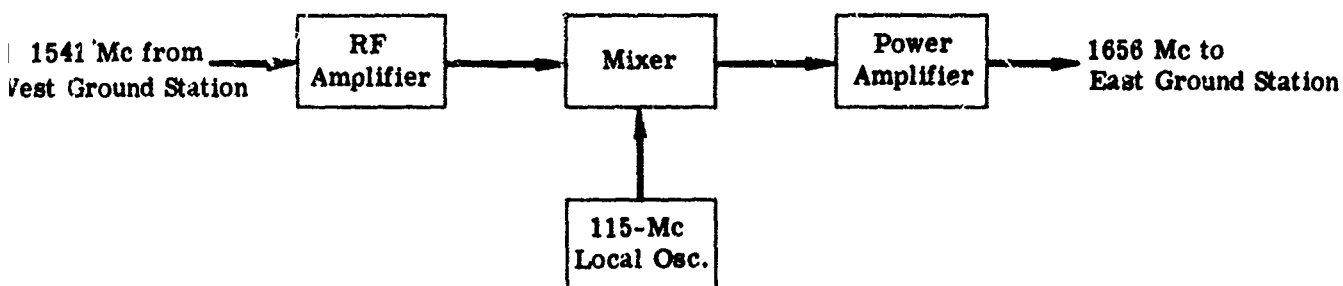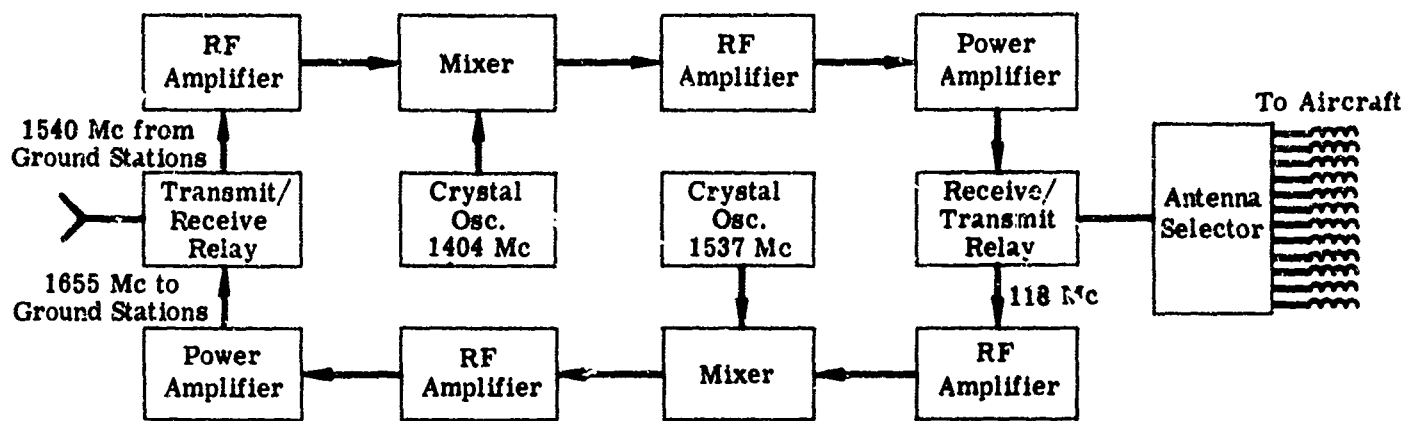
In the dotted enclosures at the bottom of Figure 28, "west-to-east" and "east-to-west" are frequency translators. An alternative satellite configuration, requiring the elimination of one of the ATSAT frequency translation packages (with an attendant reduction of reliability), would permit up to three point-to-point UHF voice links. It should be noted that these links could not provide communication with the aircraft, since there is definitely an effective power limitation between the aircraft and the satellite.

Figure 29 shows one possible configuration of the frequency translating equipment. The diagrams are self-explanatory.

Figure 30 shows a configuration of the ground-station equipment. The communication channel is at the top of the figure. The transmit-and-receive mode control determines which of the links is to be used for transmission or reception between the ground and the aircraft. It is

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[18]Such operation is used in satellites in general and, in particular, with both Telstar and Syncom.

ATCOM CHANNEL

```
┌──────────┐    ┌───────┐    ┌──────────┐    ┌──────────┐
│   RF     │───▶│ Mixer │───▶│   RF     │───▶│  Power   │
│ Amplifier│    │       │    │ Amplifier│    │ Amplifier│
└──────────┘    └───────┘    └──────────┘    └──────────┘
```

1540 Mc from Ground Stations

```
┌──────────┐    ┌───────┐    ┌───────┐    ┌──────────┐         ┌──────────┐   To Aircraft
│Transmit/ │    │Crystal│    │Crystal│    │ Receive/ │         │ Antenna  │
│ Receive  │    │ Osc.  │    │ Osc.  │    │ Transmit │─────────│ Selector │
│  Relay   │    │1404 Mc│    │1537 Mc│    │  Relay   │         │          │
└──────────┘    └───────┘    └───────┘    └──────────┘         └──────────┘
```

1655 Mc to Ground Stations

118 Mc

```
┌──────────┐    ┌──────────┐    ┌───────┐    ┌──────────┐
│  Power   │◀───│   RF     │◀───│ Mixer │◀───│   RF     │
│ Amplifier│    │ Amplifier│    │       │    │ Amplifier│
└──────────┘    └──────────┘    └───────┘    └──────────┘
```

ATCOM CHANNEL

POINT-TO-POINT CHANNEL

1541 Mc from West Ground Station

```
┌──────────┐    ┌───────┐    ┌──────────┐
│   RF     │───▶│ Mixer │───▶│  Power   │───▶ 1656 Mc to
│ Amplifier│    │       │    │ Amplifier│     East Ground Station
└──────────┘    └───────┘    └──────────┘
                    ▲
                    │
              ┌──────────┐
              │  115-Mc  │
              │Local Osc.│
              └──────────┘
```

POINT-TO-POINT CHANNEL

FIGURE 29. FREQUENCY TRANSLATORS

assumed that interlocks would be provided to keep the satellite in a mode which would permit the aircraft to transmit whenever the link was not being used to transmit a message from the ground; that is, the ground transmitter could not override an aircraft transmission.

Figure 30 also shows weather data entering the encoder. Sufficient channel capacity is available during periods between ATC messages to permit the transmission of weather data from the ground to the aircraft. The air traffic controller has access to the satellite-aircraft channels as well as to the land lines and ocean cables which are required to connect him with other ground stations. Possible point-to-point communication links that could be used in lieu of cables, etc., are dotted in. Use of these links would require eliminating one of the ATC communications packages in the satellite. The command transmitters and the telemetry receiver are shown at the bottom of the diagram.
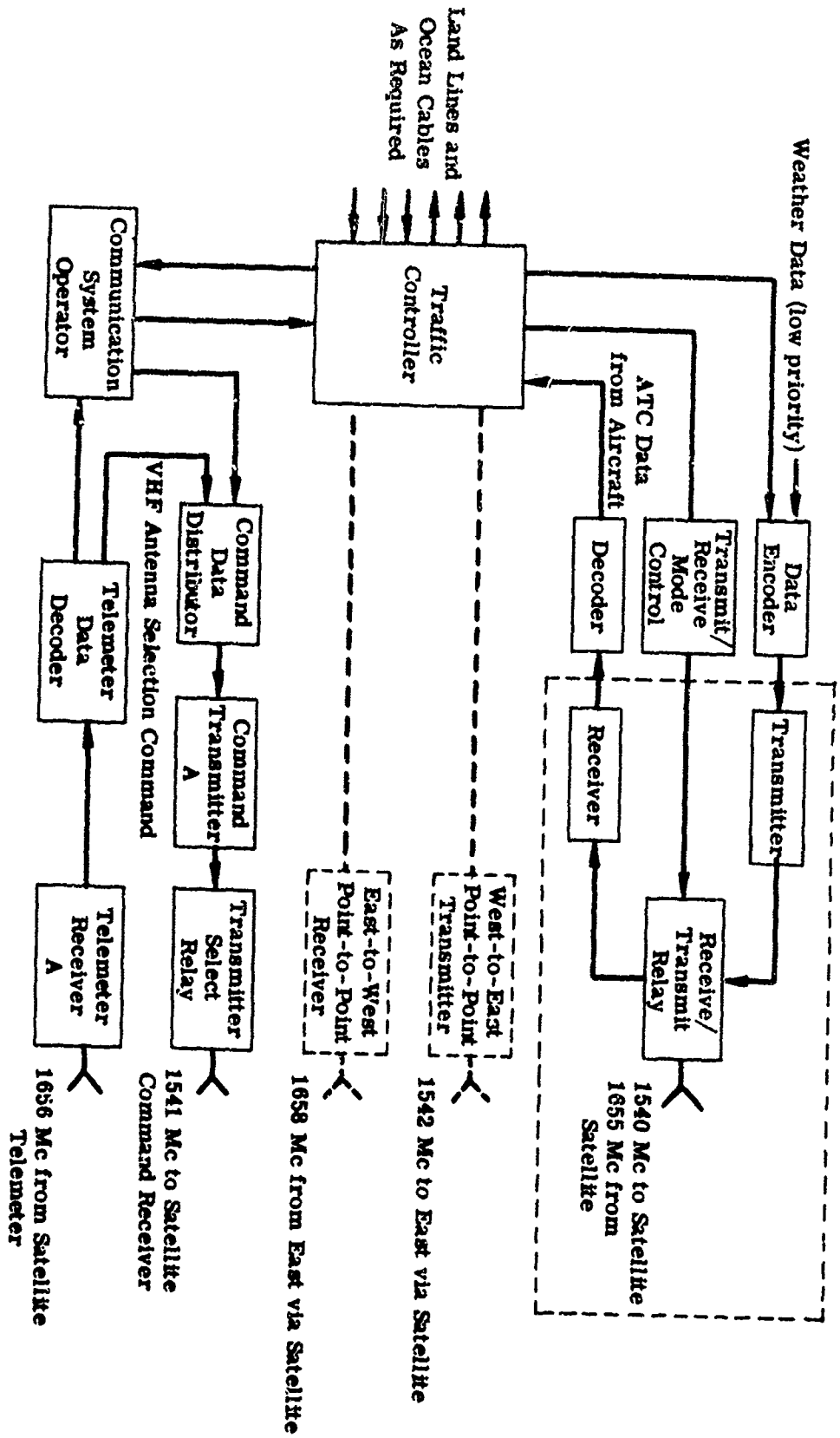
71

FIGURE 30. POSSIBLE GROUND-STATION CONFIGURATION. For simplicity, antenna multiplexing, which will be used as appropriate, has not been shown. Also, redundant equipment for reliability is not shown.

Weather Data (low priority)

Land Lines and Ocean Cables As Required

Communication System Operator

Traffic Controller

ATC Data from Aircraft

VHF Antenna Selection Command

Data Encoder

Transmit/ Receive Mode Control

Decoder

Command Data Distributor

Telemeter Data Decoder

Transmitter

Receiver

Command Transmitter

Telemeter Receiver

Receive/ Transmit Relay

West-to-East Point-to-Point Transmitter

East-to-West Point-to-Point Receiver

Transmitter Select Relay

1540 Mc to Satellite
1855 Mc from Satellite

1542 Mc to East via Satellite

1858 Mc from East via Satellite

1541 Mc to Satellite Command Receiver

1656 Mc from Satellite Telemeter

Figure 31 illustrates a possible configuration of the aircraft communications equipment. As the figure indicates, the use of present VHF transmitters and receivers for over-ocean ATC purposes is expected to continue. It will be necessary to add a VHF antenna with the required pattern to the aircraft. This probably will be a switched array, such as that discussed in Reference 18. The antenna would have a pattern providing coverage from 12° to about 58° above the horizon and have a gain of approximately 8 db. Theoretically, an antenna with a position-selector to select either the right-hand or the left-hand side of the aircraft would provide the necessary gain. However, realizable antennas may require a four-position pattern to achieve the required 8-db gain. Normally, in operation, the antenna position switch would not have to be changed during the course of the usual east-west or west-east flight path.

In addition to the present voice input and output, an output provided with a 1-kc filter to reduce the noise bandwidth drives the digital decoder. This output can be teletype or some other display format. In a future ATC system, it would be desirable to give ATC ground stations the capability of direct interrogation of the instruments aboard the aircraft. This would relieve the crew of the burden of reporting. All's-well checks, which are made regularly now, could also be made automatically. The data control box shown in Figure 31 determines when information should be transmitted and whether some of the data has priority. The data encoder merely puts the data in the proper form for digital transmission. Emergency requests might be made by use of a "panic" button with which the pilot could automatically send out a distress call.

B.1.3. PROPAGATION. This section tabulates the various propagation losses for several combinations of VHF, UHF, and SHF equipment on the ground-satellite and satellite-aircraft links. The critical links are those between the satellite and aircraft. The basic problem is the difficulty in obtaining sufficient effective power between these two points, because large, high-gain antennas cannot be used and there are, at present, severe power limitations for the satellite transmitter. In addition, the cosmic noise which both receiving antennas "see" at VHF is significant. In spite of these limitations, VHF provides the largest S/N for the satellite-aircraft links.

The tables, discussed in the next section, are based on the capabilities of the present aircraft double sideband equipment, in which it is assumed that keyed carrier modulation is available for transmitting the digital ATC data. If tone modulation is used, there is a loss of 2 db, as shown in Figure 32. If UHF or SHF equipment is used, there is no requirement that amplitude modulation be used; however, the tables have all been prepared in terms of AM so that propagation effects may be compared. Following the tables there is a discussion of the use of FM.

It is to be noted that the power rating of AM transmitters, by convention, is given in terms of carrier power. When an AM transmitter is fully modulated with a sinusoidal tone, the total power output is 1.5 times that of the unmodulated carrier. For satellite transmitters, the solar cells must provide both the carrier power and the modulating power. Therefore, it is desirable to rate these transmitters in terms of total power for determining energy requirements. The transmitter powers indicated for the satellites have been derated 1.8 db so that all transmitters are rated in terms of carrier power.
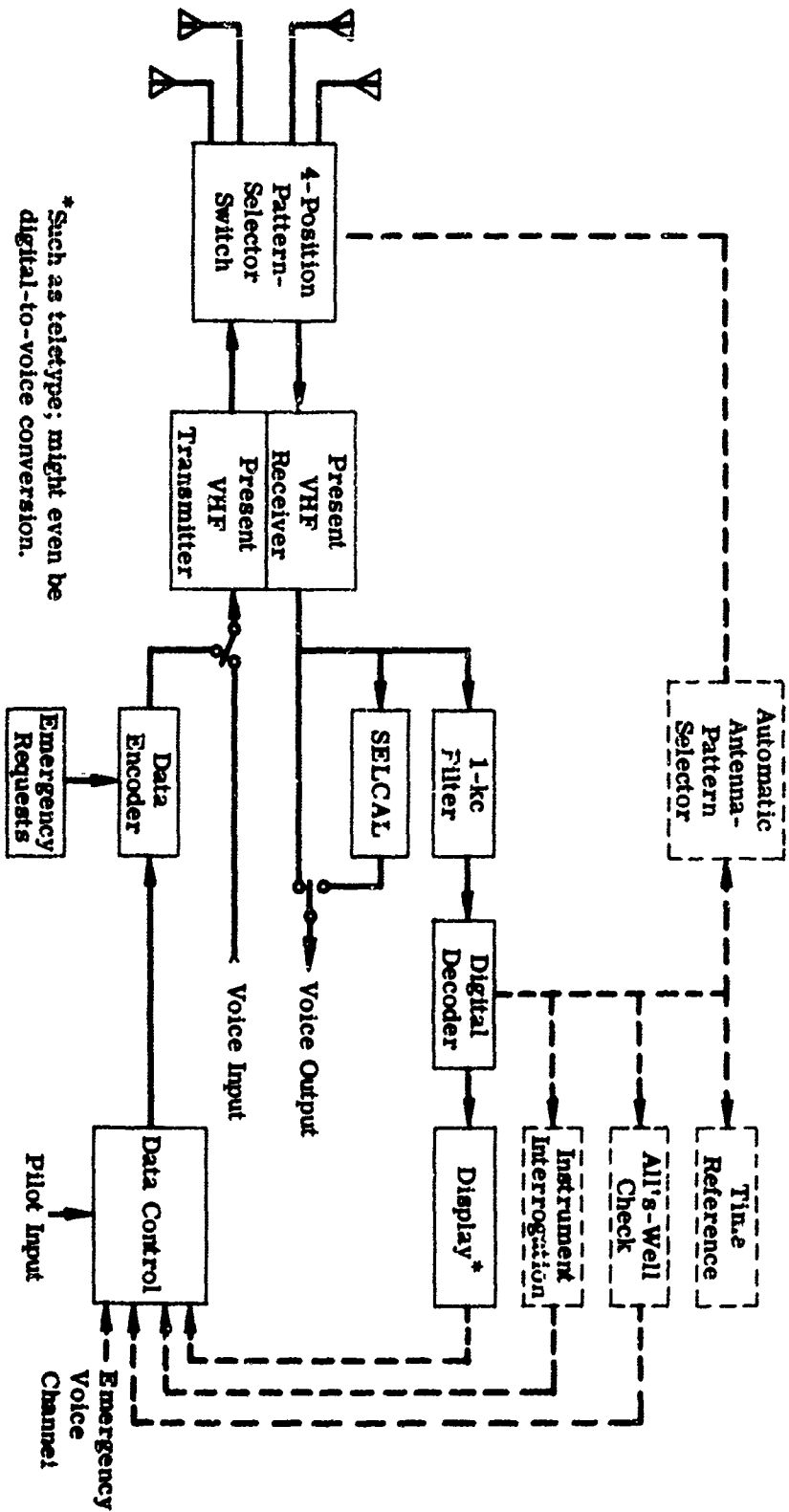
FIGURE 31. POSSIBLE AIRCRAFT-EQUIPMENT CONFIGURATION. Broken
lines are possibilities not included in the system discussion. For simplicity,
only one channel is shown.

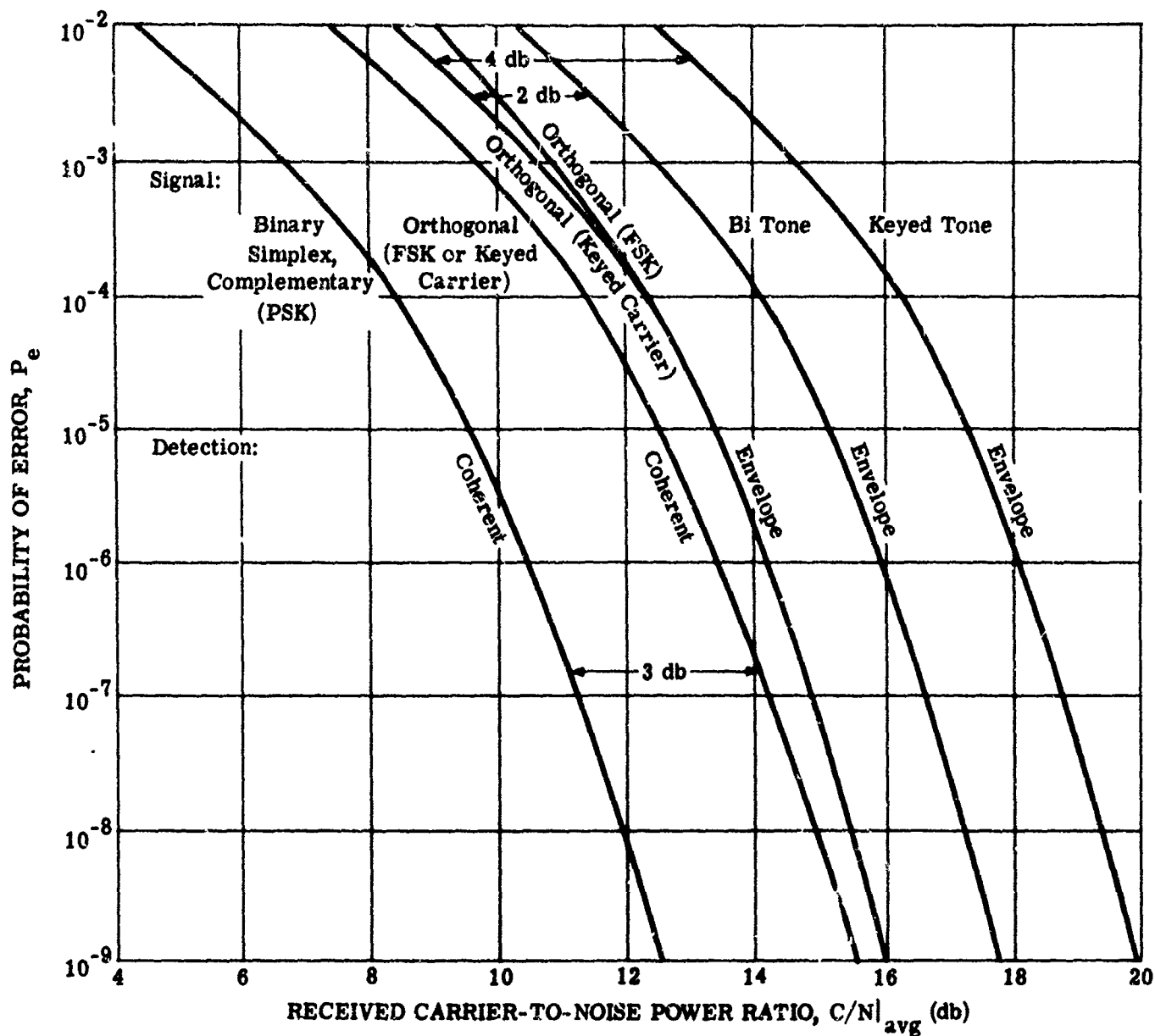*Such as teletype; might even be
digital-to-voice conversion.

FIGURE 32. PROBABILITY OF ERROR VS. CARRIER-TO-NOISE POWER
RATIO FOR BINARY SIGNALS [58, 59]

B.1.3.1. Propagation Tables. The following gives the basis for the values of the parameters
used in the propagation-power margin tables (Tables IV through VII).

Item 1. Path Length. The 25,200-mile figure is the maximum distance from a point 70°
North in the North Atlantic region to a satellite centered at approximately 30° West, 0° North
at the synchronous altitude (approximately 22,300 miles).

75

TABLE IV. ALL VHF (118-136 Mc) SATELLITE RELAY LINKS

All VHF (118-136 Mc) Satellite Relay Links 24-Hour Equatorial Orbit—Spin Stabilized	Ground to Satellite	Satellite to Ground	Aircraft to Satellite	Satellite to Aircraft
1. Path Length—Statute Miles	25,200	25,200	25,200	25,200
2. Carrier Frequency—Mc	136	136	136	136
3. Receiver Noise Figure—db	5	5	5	5
4. Equiv. Rcvr. Noise Temp.—^oK	660	660	660	660
5. Receiving Ant. Noise Temp.—^oK	3,000	8,500	2,550	3,000
6. Total Noise Temp.—^oK	3,660	9,160	3,210	3,660
7. Total Noise Temp.—db above 1^oK	35.6	39.6	35.0	35.6
8. Boltzmann's Constant—dbw/^oK/cps	-228.6	-228.6	-228.6	-228.6
9. RF Bandwidth—db above 1 cps	30	30	30	30
10. Total Receiver Noise Power—dbw	-163	-159	-163.6	-163
11. Received C/N Allow.—db	14	14	12	12
12. Required Received Carrier Power—dbw (for C/N specified in Item 11)	-149	-145	-151.6	-151
13. Transmitter Power—dbw	20	10.2	14	11.2
14. Transmitting Antenna Gain—db	25	0	8	16
15. Path Gain—db	-167	-167	-167	-167
16. Receiver Antenna Gain—db	0	25	16	8
17. Polarization Gain—db	-3	-3	-3	-3
18. Fading Margin—db	-5	-5	-5	-5
19. Sat. Ant. Switching Allow.—db	0	0	-3	-3
20. Probable Min. Recd. Carrier Power—dbw	-130	-139.8	-140	-142.8
21. Power Margin—db (Item 20 minus Item 12)	19	5.2	11.6	8.2

TABLE V. ALL UHF (1540-1660 Mc) SATELLITE RELAY LINKS

All UHF (1540-1660 Mc) Satellite Relay Links 24-Hour Equatorial Orbit—Spin Stabilized	Ground to Satellite	Satellite to Ground	Aircraft to Satellite	Satellite to Aircraft
1. Path Length — Statute Miles	25,200	25,200	25,200	25,200
2. Carrier Frequency—Mc	1,600	1,600	1,600	1,600
3. Receiver Noise Figure—db	5	5	5	5
4. Equiv. Rcvr. Noise Temp.—^{O}K	660	660	660	660
5. Receiving Ant. Noise Temp.—^{O}K	25	20	240	20
6. Total Noise Temp.—^{O}K	685	680	900	680
7. Total Noise Temp.—db above $1^{O}K$	28.3	28.3	29.6	28.3
8. Boltzmann's Constant—dbw/^{O}K/cps	-228.6	-228.6	-228.6	-228.6
9. RF Bandwidth—db above 1 cps	30	30	30	30
10. Total Receiver Noise Power—dbw	-170.3	-170.3	-169	-170.3
11. Received C/N Allow.—db	14	14	12	12
12. Required Received Carrier Power—dbw (for C/N specified in Item 11)	-156.3	-156.3	-157	-158.3
13. Transmitter Power—dbw	20	-1.8	14	11.2
14. Transmitting Antenna Gain—db	40	6	8	17
15. Path Gain—db	-190	-190	-190	-190
16. Receiver Antenna Gain—db	6	40	17	8
17. Polarization Gain—db	0	0	-3	-3
18. Fading Margin—db	0	0	0	0
19. Sat. Ant. Switching Allow.—db	0	0	-3	-3
20. Probable Min. Recd. Carrier Power—dbw	-124	-145.8	-157	-159.8
21. Power Margin—db (Item 20 minus Item 12)	22.3	10.5	0	-1.5

77

TABLE VI. ALL SHF (5000-5250 Mc) SATELLITE RELAY LINKS

All SHF (5000-5250 Mc) Satellite Relay Links 24-Hour Equatorial Orbit—Spin Stabilized	Ground to Satellite	Satellite to Ground	Aircraft to Satellite	Satellite to Aircraft
1. Path Length—Statute Miles	25,200	25,200	25,200	25,200
2. Carrier Frequency—Mc	5,000	5,000	5,000	5,000
3. Receiver Noise Figure—db	5	5	5	5
4. Equiv. Rcvr. Noise Temp.—^{0}K	660	660	660	660
5. Receiving Ant. Noise Temp.—^{0}K	20	10	180	0
6. Total Noise Temp.—^{0}K	680	670	840	660
7. Total Noise Temp.—db above 1^0K	28.3	28.3	29.3	28.2
8. Boltzmann's Constant—dbw/^{0}K/cps	-228.6	-228.6	-228.6	-228.6
9. RF Bandwidth—db above 1 cps	30	30	30	30
10. Total Receiver Noise Power—dbw	-170.3	-170.3	-169.3	-170.4
11. Received C/N Allow.—db	14	14	12	12
12. Required Received Carrier Power—dbw (for C/N specified in Item 11)	-156.3	-156.3	-157.3	-158.4
13. Transmitter Power—dbw	20	-1.8	14	8.2
14. Transmitting Antenna Gain—db	40	6	8	17
15. Path Gain—db	-199	-199	-199	-199
16. Receiver Antenna Gain—db	6	40	17	8
17. Polarization Gain—db	0	0	-3	-3
18. Fading Margin—db	0	0	0	0
19. Sat. Ant. Switching Allow.—db	0	0	-3	-3
20. Probable Min. Recd. Carrier Power—dbw	-133	-154.8	-166	-171.8
21. Power Margin—db (Item 20 minus Item 12)	23.3	1.5	-8.7	-13.4

TABLE VII. FEASIBLE SATELLITE RELAY LINK

Feasible Satellite Relay Link 24-Hour Equatorial Orbit—Spin Stabilized	Ground to Satellite	Satellite to Ground	Aircraft to Satellite	Satellite to Aircraft
1. Path Length—Statute Miles	25,200	25,200	25,200	25,200
2. Carrier Frequency—Mc	1,600	1,600	136	136
3. Receiver Noise Figure—db	5	5	5	5
4. Equiv. Rcvr. Noise Temp.—^{O}K	660	660	660	660
5. Receiving Ant. Noise Temp.—^{O}K	25	20	2,550	3,000
6. Total Noise Temp.—^{O}K	685	680	3,210	3,660
7. Total Noise Temp.—db above 1^{O}K	28.3	28.3	35.0	35.6
8. Boltzmann's Constant—dbw/^{O}K/cps	-228.6	-228.6	-228.6	-228.6
9. RF Bandwidth—db above 1 cps	30	30	30	30
10. Total Receiver Noise Power—dbw	-170.3	-170.3	-163.6	-163
11. Received C/N Allow.—db	14	14	12	12
12. Required Received Carrier Power—dbw (for C/N specified in Item 11)	-156.3	-156.3	-151.6	-151
13. Transmitter Power—dbw	20	-1.8	14	11.2
14. Transmitting Antenna Gain—db	40	6	8	16
15. Path Gain—db	-190	-190	-167	-167
16. Receiver Antenna Gain—db	6	40	16	8
17. Polarization Gain—db	0	0	-3	-3
18. Fading Margin—db	0	0	-5	-5
19. Sat. Ant. Switching Allow.—db	0	0	-3	-3
20. Probable Min. Recd. Carrier Power—dbw	-124	-145.8	-140	-142.8
21. Power Margin—db (Item 20 minus Item 12)	32.3	10.5	11.6	8.2

Item 2. Carrier Frequency. The FAA Frequency Management Division has indicated that frequencies in the VHF (118-136 Mc) band, the UHF (1540-1660 Mc) band, and the SHF (5000-5250 Mc) band could be made available for this service without much difficulty. Since these frequencies seem to provide adequate choice, no other frequencies have been considered. For reliable communications over long atmospheric path lengths, frequencies above 6000 Mc are of little interest because of the signal attenuation produced by rainfall, and frequencies below 118 Mc are of little interest because they require antennas too large for practical use on satellites or aircraft (for reasonable antenna-gain figures). In addition, frequencies below this range are unsuitable because of noise and other problems of propagation.

Item 3. Receiver Noise Figure. Receiver noise figures of 5 db (660°K) have been used in all calculations, even though noise figures in the 3-db region have been quoted for aircraft equipment. (Aircraft noise should also be considered in a discussion of very low noise figures in the aircraft environment.) In the satellite-to-aircraft link, which is the most critical of the communication links for this ground-to-satellite-to-aircraft communication system, reducing the receiver-noise figure from 5 db to 3 db would reduce the total noise temperature acting on a communication system by only 0.5 db at VHF (i.e., cosmic noise controls).

Item 4. Equivalent Receiver Noise Temperature. Equivalent receiver noise temperature has been obtained from Figure 33.

Item 5. Receiving Antenna Noise Temperature. Receiving antennas located on the ground or on the aircraft and looking upward to satellites will look at cosmic noise. Figure 22 shows
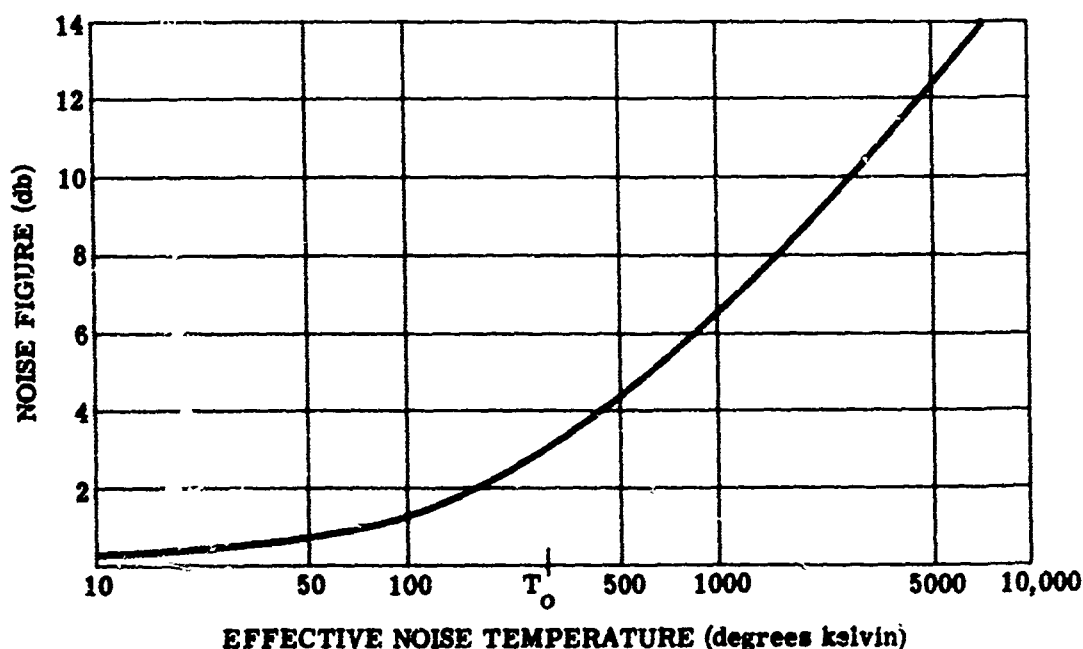
FIGURE 33. RECEIVER NOISE

that the temperature of this noise is between 500°K and 6000°K at 1.0 Mc. Since the higher noise temperatures rarely occur, the 3000°K figure is used. (For a 10° beamwidth at 136 Mc, the maximum cosmic noise, not including that from the sun, never exceeds 3000°K; including that from the sun, the maximum cosmic noise may be as high as 8500°K.) Above 1000 Mc the cosmic noise is always less than 10°K and is negligible for 1600- and 5000-Mc receivers on the ground and in the aircraft. Antennas viewing the earth from the satellite will see a combination of the earth's temperature, the cosmic noise temperature, and the noise from the sun at some time of the day, depending on the antenna beamwidth. If the antenna beamwidth just covers the earth, the apparent temperature will be that of the earth, or about 300°K. As the antenna beamwidth increases, the effective temperature will rise at the VHF frequencies because of the 3000° cosmic noise and solar noise, and will fall at the 1600- and 5000-Mc frequencies because the cosmic noise is essentially 0° while the effects of the sun are still present. These effects are shown in Figure 34.

Item 6. Total Noise Temperature. The total noise temperature acting on the receiver is a combination of Items 4 and 5.

Item 7. Total Noise Temperature. This is the noise temperature expressed in db above 1°K.

Item 8. Boltzmann's Constant. This is the noise power density, or Boltzmann's Constant in dbw/°K/cps.

Item 9. RF Bandwidth. An information bandwidth of only 500 cps is required to meet the requirements for ATC data. Since the present equipment is double sideband AM, an RF bandwidth of 1 kc is required. The actual data-channel-capacity requirements are discussed in Section 3.2.

Item 10. Total Receiver Noise Power. This is the sum of Items 7, 8, and 9, and will ultimately determine the minimum usable received signal.

Item 11. Received C/N Allowance. A received carrier-to-noise ratio (C/N) of 12 db gives a probability of error of about 10^{-4} for a keyed carrier envelope-detection, digital-transmission system operating in the presence of white gaussian noise (Figure 32). Since the aircraft-to-satellite link appears to be the most critical, setting the design criteria of the system so that the C/N is always at least 12 db makes a larger C/N necessary for the ground-satellite link. If the probability of error for the ground-satellite links alone is two orders of magnitude less than for the satellite-aircraft links, then, for practical purposes, all errors result from errors in the aircraft-satellite link. Thus, a received signal C/N for the satellite-to-ground links of 14 db must be used; it yields a probability of error of 10^{-6}.

Item 12. Required Received Carrier Power. This is the algebraic sum of Items 10 and 11.

Item 13. Transmitter Power. Power transmitted from the ground has been held to values considered very modest. At all frequencies, 100 watts (20 dbw) is assumed to be available on the ground.
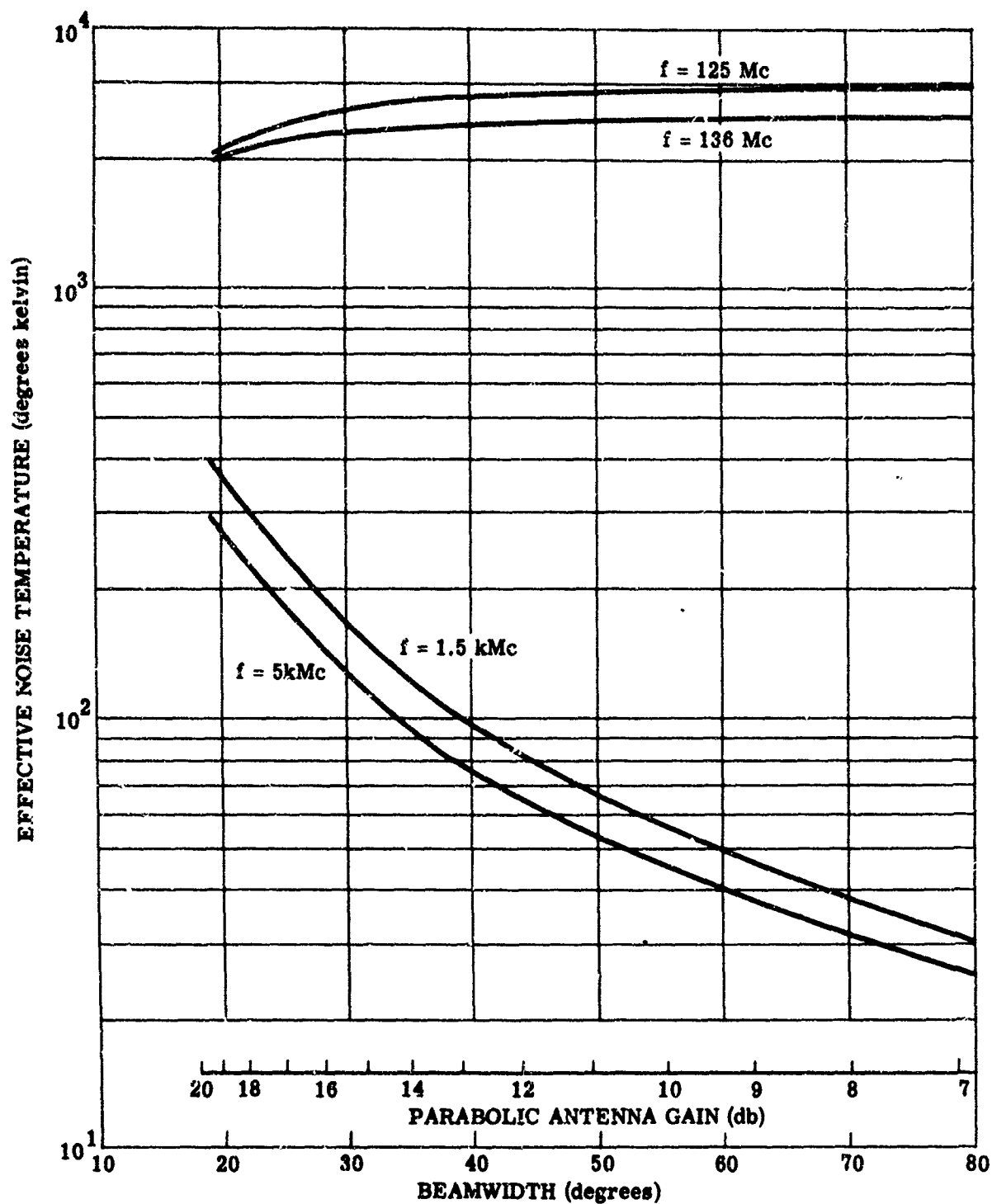
FIGURE 34. SYNCHRONOUS SATELLITE ANTENNA NOISE TEMPERATURE.
Ideal antenna pointed at earth. The effects of cosmic noise and solar noise
(quiet conditions) are included. Note: The discontinuities in the range imme-
diately above 18° of beamwidth are a result of the simp' lied antenna assump-
tions (i.e., 100% efficient conical beam). Exact results in this region require
detailed knowledge of antenna pattern and side-lobe offects.

Commercial aircraft use VHF transmitters with 25 watts (14 dbw) of output power. There is little indication that additional power is required to satisfactorily operate the link from aircraft to satellite, even at VHF.[19] For 1600 Mc and 5000 Mc, it is assumed that the maximum power available from the aircraft would be 25 watts (14 dbw). Transmitter power for the satellite-to-ground link is 15 watts (12 dbw) at VHF and 1 watt (0 dbw) at 1600 Mc and 5000 Mc.

For the satellite-to-aircraft link, the maximum power available at 1600 Mc and 5000 Mc in a satellite is assumed to be 20 and 10 watts respectively. At VHF, two independent 20-watt (13 dbw) transmitters are provided. Forty watts of VHF power (total) would probably require no more solar cells or weight in the satellite than would 20 watts (or less) of 1600-Mc equipment or 10 watts of 5000-Mc equipment.

Item 14. Transmitting Antenna Gain. The ground transmitting antenna is not critical at any of the frequencies; it is assumed that for reasons of economy this antenna would be limited to a maximum of 60 feet, or 40 db, to maintain a moderate beamwidth and reduce tracking requirements if the "stationary" satellite drifts by small amounts. The 60-foot limit is used at VHF (25 db, 10° beam). The 40-db (2°) limit is used at UHF and SHF.

The antenna for the aircraft should have a biconical upward-directional pattern which extends from about 12° to 58° above the horizon. In theory, such an antenna, with an omnidirectional pattern in the horizontal plane, can have a gain of 5 db; an additional 3 db can be expected if the antenna pattern is divided into two 180° segments. This type of antenna would not normally have to be switched during the course of a North Atlantic flight. Practical difficulties might necessitate selecting one of four quadrants of the antenna pattern to obtain the necessary 8-db gain. Aircraft antennas with comparable gains have been discussed in the literature [60].

The antenna for the satellite-to-aircraft link requires more gain than the other satellite-mounted antenna in the proposed ATSAT system. The minimum beamwidth it can have is 18°, as this will just cover the earth at the synchronous altitude. To allow for stabilization errors, an antenna with a 30° beamwidth and a gain of 16 db is used. A concept of an antenna, which will be deployed once the vehicle is in orbit, is shown in Figure 35. Since the satellite, by definition, operates in zero gravity, the mechanical problems of its size are not serious [57].

The UHF and/or SHF antennas for the satellite-ground link are relatively small and simple because of the high frequencies involved. A gain of 6 db has been assumed, which is of the order used in Syncom.

Item 15. Path Gain. The free space attenuation losses for the frequencies involved are shown in Figure 24.

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[19]Aircraft power amplifiers in the 1- to 5-kw range have been successfully operated in several experimental VHF and UHF scatter programs. Thus, the technology is available if increased power is required.
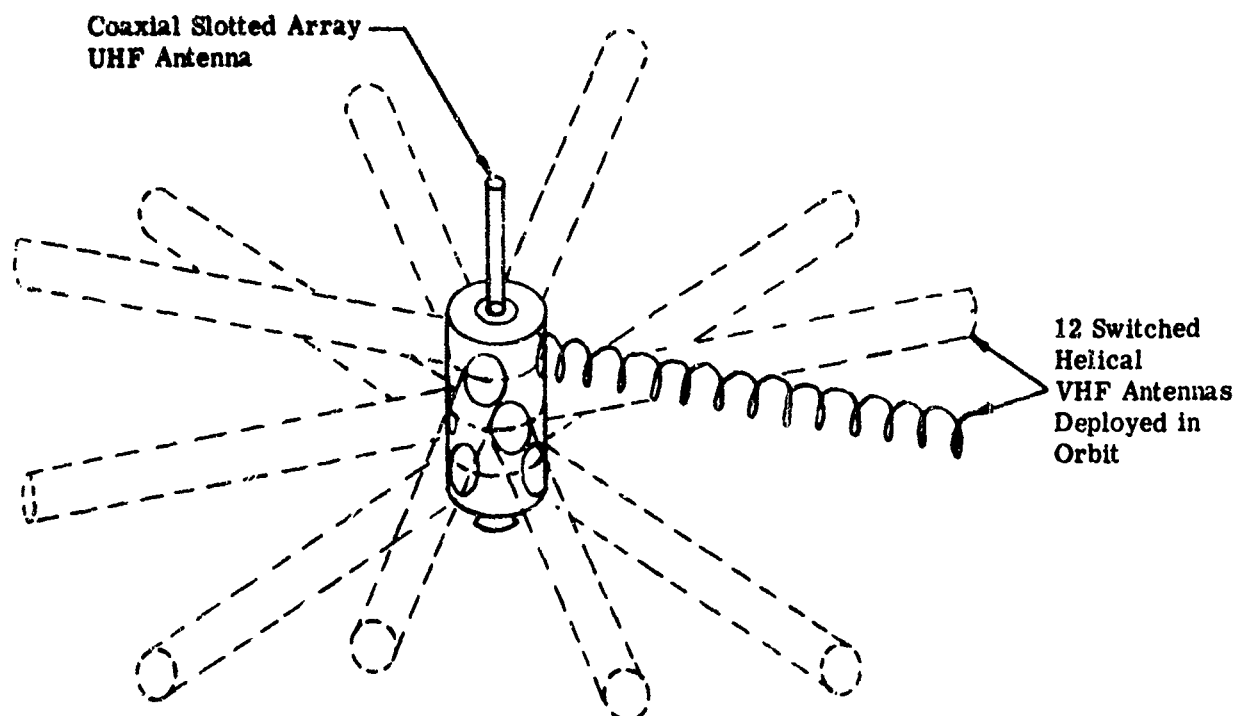
Coaxial Slotted Array —
UHF Antenna

12 Switched
Helical
VHF Antennas
Deployed in
Orbit

FIGURE 35. POSSIBLE ATC COMMUNICATIONS SATELLITE THAT IS SPIN-
STABILIZED

Item 16. Receiver Antenna Gain. Since each antenna is used for both receiving and trans-
mitting, the various antennas have already been discussed under Item 14.

Item 17. Polarization Gain. Because the relative attitude of the aircraft with respect to
the satellite is changing, circular polarization must be used. However, circularly-polarized
antennas are impractical on the aircraft and can be used only on the satellite. Therefore, a
3-db polarization loss will occur on this link. There is no relative motion between antennas
in the satellite-ground links which would cause serious misalignment of the planes of polariza-
tion. However, Faraday rotation may be significant in the VHF region and circularly polarized
antennas should be provided for at least one end of this link. Since it is not deemed practi-
cal to have a second large circularly-polarized VHF antenna on the satellite, a 3-db polarization
loss must be accepted for the VHF ground-satellite links.

Item 18. Fading Margin. In general, fading is not a problem at 1500 to 5000 Mc; there-
fore, no allowance is made for the ground-to-satellite links. A 5-db fading margin has been
allowed for the VHF propagation case, since some fading does take place during extreme solar
activity.

Item 19. Satellite Antenna Switching Allowance. Since it is necessary to use several
switched VHF antennas in the satellite in order to achieve enough gain, some loss in switching

is anticipated.[20] It would appear that if sealed antenna coaxial relays could be used, this loss could be made arbitrarily small. However, the use of switching methods introduces problems of power and reliability. Perhaps some other, less efficient (in the RF sense) means might be used. For this reason a switching allowance of 3 db has been assumed.[21]

Item 20. Probable Minimum Received Carrier Power. This is the algebraic sum of Items 13 through 19.

Item 21. The Power Margin. The power margin is the difference between the received signal power (Item 12) and the receiver noise power (Item 10). In effect, this power is available to compensate for any losses which have not otherwise been taken into account. Note that any of the three frequencies are usable from a propagation standpoint for the satellite-ground links, but only VHF is suitable for the satellite-aircraft links.

B.1.3.2. Voice Link. An emergency voice channel would require a 3-kc audio bandwidth as compared to the 500-cps data channel.[22] The increased noise bandwidth reduces the received $S_o/N|_B$ for the critical satellite-to-aircraft path (Table VII) by a factor of 6 (7.8 db). Item 20 minus Item 10 yields a received $C/N|_{2B}$ of 20.2 db for the 500-cps channel with zero power margin. The 7.8 db required to provide the voice channel bandwidth reduces the $C/N|_{2B}$ to 12.4 db. Since $S_o/N|_B$ for a double sideband AM system is equal to $C/N|_{2B}$, and since an S_o/N of 20 db is considered desirable for voice communications, it is apparent that some modulation technique other than DSB-AM is required if these higher signal-to-noise ratios are to be achieved without increasing transmitter power.[23] Two modulation techniques which provide the required advantage over conventional AM are discussed in the following paragraphs.

The discussion of frequency modulation systems will be facilitated by a tabulation of the general formulas applying to both conventional and feedback FM (FBFM) [65 - 70]. Note that expressions for conventional and feedback FM are identical if $F = 1$. Hereafter, the more general FBFM form will be used.

The RF bandwidths are based on the widely used approximation that an FM signal of modulation index M can be recovered from an i-f signal of $2B(1 + M)$ bandwidth without objectionable distortion. The $3M^2$ factor in the expression for output signal-to-noise ratio is commonly known as

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[20] The Hughes Syncom II communications satellite is expected to use a phased array which also has to be switched [61].

[21] When attitude-stabilized satellites are available, only one antenna will be required; thus, there will be no switching losses (Figure 36).

[22] Note that the use of a voice channel would necessitate interrupting all data transmission.

[23] About 90% intelligibility of sentences is expected with 15 db S_o/N [62]; for commercial quality circuits, 29 db is accepted, and 39 db is required for broadcast quality [63, 64].

TABLE VIII. EQUATIONS FOR CONVENTIONAL AND FEEDBACK FM

	Conventional FM	Feedback FM	
RF Bandwidth, cps	$2B(1 + M)$	$2B(1 + M)$	(4)
i-f Bandwidth, cps	$2B(1 + M)$	$2B(1 + M/F)$	(5)
$C/N\vert_{2B}$, db	$10 \log \frac{P}{2Bn}$	$10 \log \frac{P}{2Bn}$	(6)
$C/N\vert_{i-f}$, db	$10 \log \frac{P}{2B(1 + M)n}$	$10 \log \frac{P}{2B(1 + M/F)n}$	(7)
$C/N\vert_{i-f}$, db	$C/N\vert_{2B} - 10 \log (1 + M)$	$C/N\vert_{2B} - 10 \log (1 + M/F)$	(8)

$$S_o/N\vert_B, \text{ db} \quad 10 \log \left(\frac{P}{2Bn}\right) 3M^2 = C/N\vert_{2B} + 10 \log 3M^2 \quad (\text{only if } C/N\vert_{i-f} > 11.8 \text{ db}) \qquad (9)$$

P = received carrier power

B = base or audio bandwidth

M = modulation index

n = noise power spectral density (watts/cps)

N = product of noise power spectral density and noise bandwidth

F = feedback factor, by convention defined as:

$$F = 20 \log \left(\frac{\text{modulation index without feedback}}{\text{modulation index with feedback}}\right) - \text{db}$$

$C/N\vert_{i-f}$ = carrier-to-noise ratio in the i-f bandwidth

$C/N\vert_{2B}$ = carrier-to-noise ratio referred to a bandwidth of $2B$ (for convenient comparison to DSB-AM)

$S_o/N\vert_B$ = the output signal-to-noise ratio (= to $C/N\vert_{2B}$ for DSB-AM)

the FM improvement factor (over DSB-AM). However, it is essential to recognize that this "improvement" is not realized unless the $C/N\vert_{i-f}$ is maintained above a minimum or threshold value. This threshold has been determined by subjective experiments to occur at $C/N\vert_{i-f} = 15$ (11.8 db). (Also, it should be pointed out that the $3M^2$ factor is strictly applicable only to random noise and does not apply to impulsive noise.) Thus:

$$\text{Threshold } C/N\vert_{2B} = 11.8 \text{ db} + 10 \log (1 + M/F) \qquad (10)$$

Examination of Equation 9 indicates that for an FM system to offer an advantage over DSB-AM, an M greater than 0.57 is required (i.e., since $S_o/N\vert_B = (P/2Bn_o) 3M^2$, $3M^2$ must be > 1 and $M > 0.57$).

86

Solar-Cell Paddle

UHF Parabolic Antenna

VHF Helical Antenna
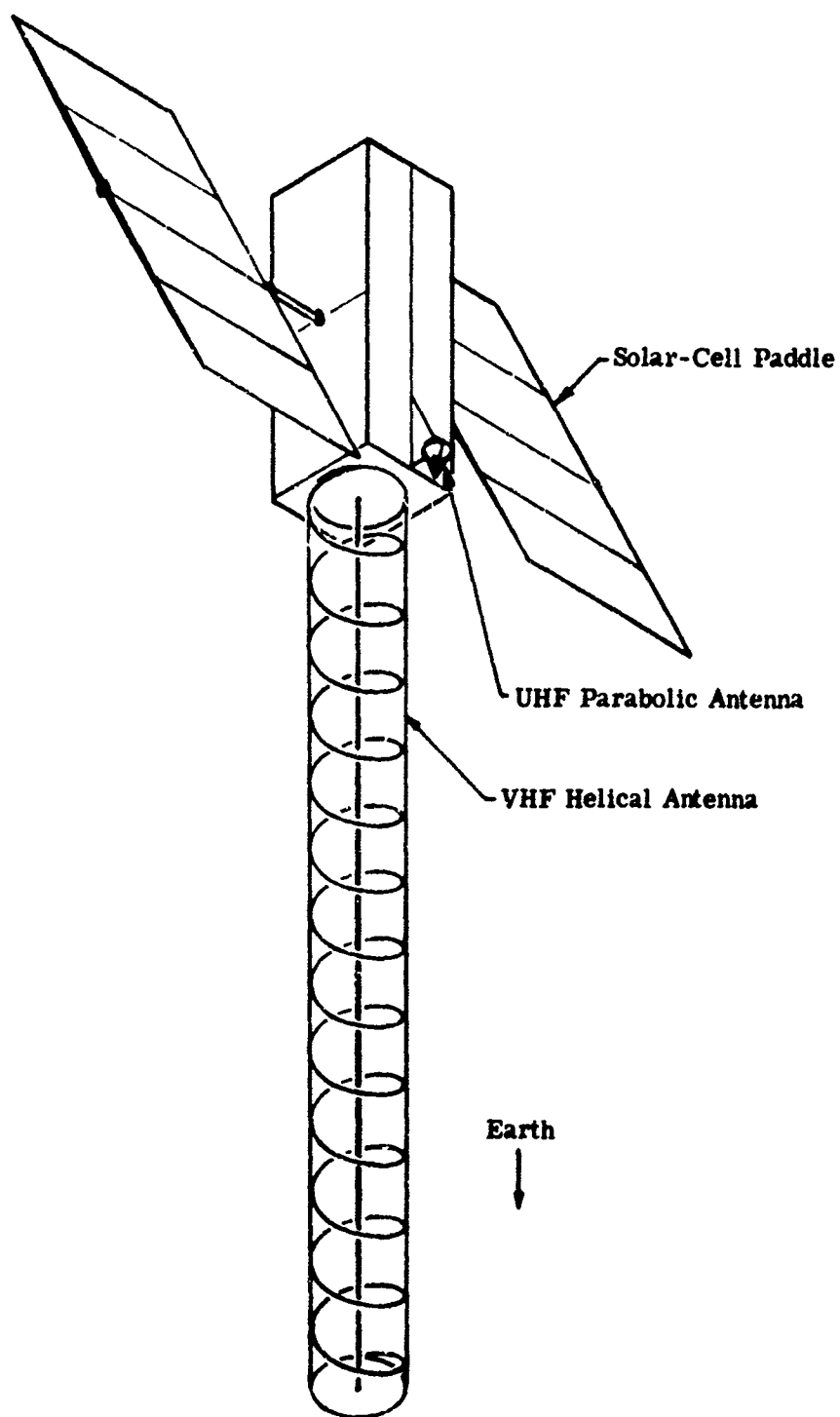
Earth

FIGURE 36. POSSIBLE ATC COMMUNICATIONS SATELLITE. Earth orientated.
Note: antennas and paddles deployed in orbit.

87

As noted previously, a voice channel $C/N|_{2B}$ of 12.4 is available. For a conventional FM system, then, with $M = 0.57$ and $C/N|_{2B} = 12.4$ db,

$$C/N|_{i-f} = 12.4 - 10 \log (1 + 0.57) = 10.44 \text{ db} \qquad (11)$$

Thus, conventional FM will not provide a usable voice link since the threshold requirements cannot be met.

Feedback FM, however, provides a means of reducing the noise bandwidth in the i-f and thus effectively lowers the threshold C/N required in the reference bandwidth, 2B.

Table IX presents four examples of FBFM systems and, for comparison, a conventional FM system (i.e., $F = 1.0$).

TABLE IX. COMPARISON OF FEEDBACK FM SYSTEMS

Case		I	II	III	IV	V
		25-kc RF BW Systems			Minimum RF BW System for 20 db S_o/N	Wide Band-width $F = \infty$ System
		$F = 1$	$F = 20$	$F = \infty$		
B	kc	3.00	3.00	3.00	3.00	3.00
M	numeric	3.16	3.16	3.16	1.38	100.00
F	numeric (db)	1.00 (0 db)	20.00 (26 db)	∞	8.66 (18.8 db)	∞
RF BW	kc	25.00	25.00	25.00	14.30	606.00
i-f BW	kc	25.00	6.95	6.00	6.95	6.00
$C/N|_{i-f}$	db	6.20	11.80	12.40	11.80	12.40
$C/N|_{2B}$	db	12.40	12.40	12.40	12.40	12.40
$10 \log 3M^2$	db	$C/N|_{i-f}$ is below threshold	14.80	14.80	7.60	44.80
$S_o/N|_B$	db	--	27.20	27.20	20.00	57.20

Note: (1) Transmitter power held constant for all cases.

(2) A $C/N|_{2B}$ of 20.2 db is available for the 500-cps DSB-AM data channel or 12.4 db for a 3-kc DSB-AM voice channel (i.e., $20.2 - 10 \log \frac{3000}{500}$). These values are based on zero power margin.

The first three examples in Table IX are based on 25-kc RF bandwidth. Case 1, conventional FM, fails to provide the required threshold C/N in the i-f and is therefore not feasible (since RF bandwidth is expanded by a factor of 4.16 (6.2 db) over 2B, the $C/N|_{i-f}$ is lowered to 12.4 - 6.2 = 6.2 db).

In Case 2, with the same M and RF bandwidth, a feedback factor of 20 reduces the i-f bandwidth to 6.95 kc and just maintains the threshold $C/N|_{i-f}$ of 11.8 db. Though an output S_o/N of 27.2 db is achieved, it should be recognized that even a small reduction in $C/N|_{i-f}$ will drop the system below threshold and the output S/N will be degraded disastrously.

Case 3, utilizing infinite feedback, yields the same $S_o/N|_B$ at the design operating point; however, in this case, the $C/N|_{i-f}$ is maintained at 0.6 db above threshold by virtue of the narrower 6-kc i-f bandwidth. Thus, a decrease in signal power of 0.6 db can be tolerated before dropping below the threshold. (Note that the $S_o/N|_B$ will drop by the same amount to 26.6 db.) This slight power margin is all that is gained by increasing the feedback from 20 to infinity.

Case 4 illustrates the FBFM values for a minimum RF bandwidth system which provides the desired 20 db $S_o/N|_B$ with no margin (Figure 37). Again, any slight loss of received signal will drop the system below threshold.

Case 5 illustrates the benefits which, in principle, can be realized with very large amounts of feedback if unlimited bandwidth is available. Since, for infinite feedback, the i-f bandwidth remains at 2B, the $C/N|_{i-f}$ is maintained at 12.4 db, no matter what value of modulation index M is used. With an FM improvement of $3M^2$, it is, in theory, possible to obtain any output signal-to-noise ratio desired. For the example chosen, an M of 100 yields an $S_o/N|_B$ of 57.2 db. Again it should be noted that no more than 0.6 db drop in signal power can be tolerated. The 606-kc bandwidth is obviously somewhat impractical in the crowded VHF region. Even more to the point, however, are the practical difficulties encountered in realizing stable physical systems for extreme values of feedback.

For the problem at hand, it would appear that FBFM could be best utilized at modest values of F; i.e., 10 to 20 db (to increase S_o/N) in conjunction with relatively small increases in transmitter power to bring the system to an operating point comfortably above the threshold. Such advances in output-power capability are to be anticipated as satellite development proceeds.

The use of SSB with an advantage over AM of approximately 10 db is an alternative way of achieving an output S/N of at least 20 db. Even though its advantage over AM cannot be increased as in FM, it does have the advantage of requiring appreciably less bandwidth than FM systems.

Since both FBFM and SSB can meet the 20-db requirement, it is difficult to say that one is appreciably superior to the other. In the opinion of the authors, such a decision depends on equipment techniques that are selected for domestic ATC and a detailed cost comparison between the two. This need not delay work on a satellite system since the system can be designed to accommodate the wideband case at small additional cost. If the narrowband SSB is selected later, it will be compatible and will not affect the overall satellite relay performance.
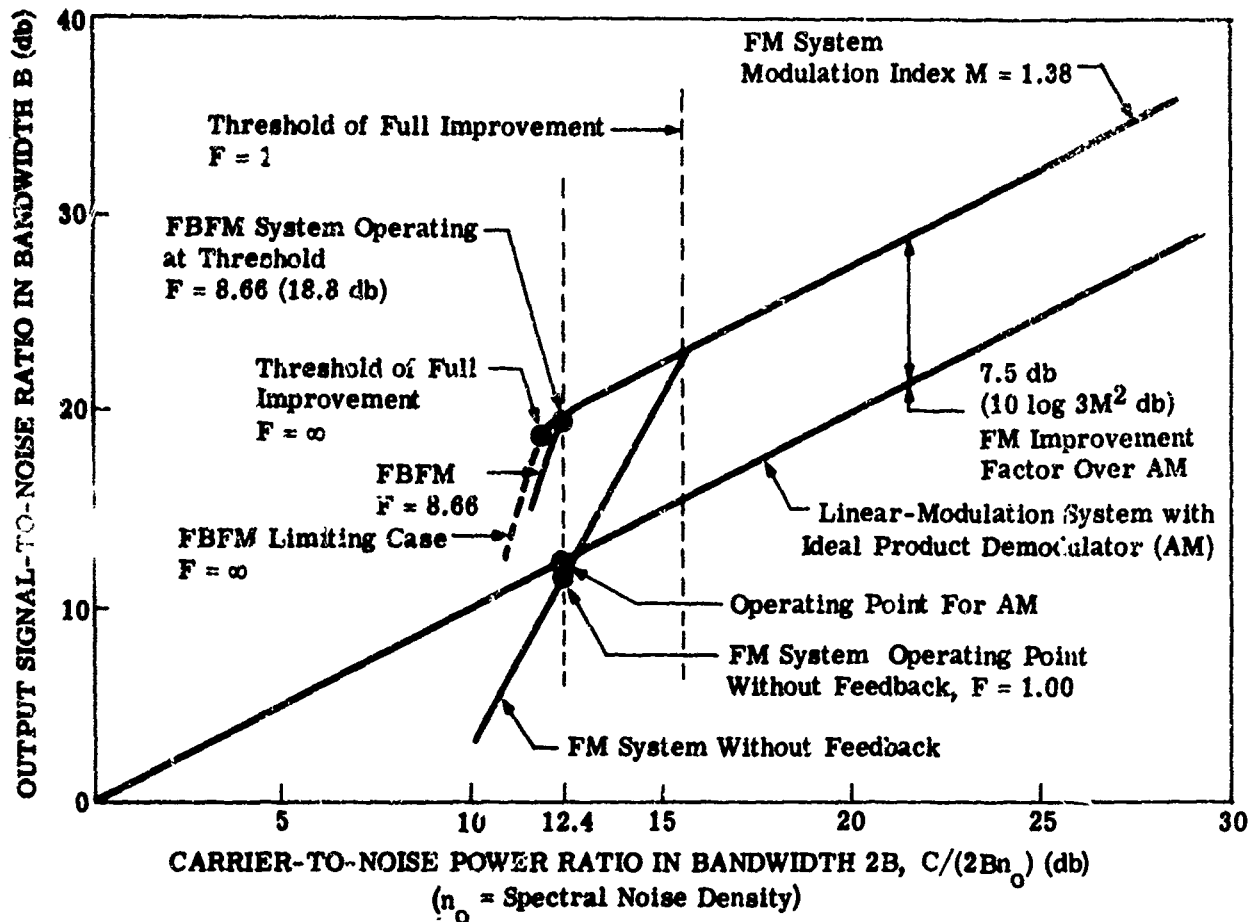
FIGURE 37. OUTPUT AND THRESHOLD CHARACTERISTICS FOR FM AND
FBFM

B.1.4. COSTS. Satellite equipment, as opposed to earth or aircraft-based equipment, has
no salvage value if it fails during launch, or after it has been in orbit for some time. There-
fore, the principal cost of installing and maintaining a satellite communication system is not
fixed, but lies in a range of values. The costs are best described in terms of random variables
with probability distributions. The number of launches required to inject a satellite into orbit
and the length of time it is expected to function properly, are the variables to be described.
The average annual cost (C) of keeping n satellites in orbit is

$$C = \frac{nc}{PT}$$

where c = the cost per launch, regardless of the success of the launch

P = the probability of successful launch

T = the expected lifetime (in years) of the vehicle once it is in orbit

Because of the necessarily large size of the ATSAT, only the Atlas-Agena vehicle combination is adequate at present for injection into medium or synchronous orbit. A breakdown of the 10-million dollar launch costs (9.7 million for medium altitudes) is given in Table X.[24]

TABLE X. ATLAS-AGENA COSTS

Satellite Costs	Millions of Dollars
Launch of Basic Atlas-Agena (without payload)	7.5
Estimated Communication Equipment	0.2
Power Supply (solar cells, batteries, regulators)	0.4
Tracking and Orbit Determination	0.6
Integration of the Satellite with the Launch Vehicle (including the protective launch shroud and the later satellite ejection)	1.0
Station-Keeping Equipment (not required for medium-altitude satellites)	0.3
Launch Cost for a 24-Hour Equatorial Orbit	10.0

Feldman suggests that the probability of a successful launch in 1965-1970 will be 0.8 for medium-altitude satellites and 0.6 for synchronous satellites, because of their greater complexity [71]. By 1970, the mean time to failure of a satellite is expected to be at least 5 years; this is the value that is used in all calculations.

The number of satellites in orbit will be more than required for communications purposes; this is necessary to prevent service from being disrupted while a satellite is being replaced. The number of satellites required is a function of the mean time to failure and the time to prepare a vehicle for launch. For the Atlas-Agena, the preparation time — the so-called, turn-around time — is expected to be reduced to six weeks by 1970.

From an expression developed by Feldman, it can be shown that with a mean time to failure of 5 years and a turn-around time of 6 weeks, the probability that the remaining satellite of a two-satellite system will fail before the first satellite can be replaced is 0.024 (assuming an orbital injection probability of 1). Since this probability is very small, two satellites in

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[24] The cost and reliability data came from personal communications with personnel at the Rand Corporation, Hughes Aircraft, Bell Telephone Laboratories, NASA Headquarters (Office of Applications), and the Advent Management Agency. Because some of the data may be proprietary, they should be considered for official government use only.

orbit for each one required for communications purposes will be assumed for the synchronous case. Also, since the medium-altitude satellites are in random orbits and the loss of one of 30 satellites will reduce the capacity of the system about 3%, the two-for-one system is not used for estimating the costs. Further, since the medium-altitude ATCOM would constitute only about one-half the possible booster load, it is assumed that only one-half the cost must be borne by the ATC system.

Medium-Altitude $\qquad \frac{1}{2} \frac{30 \times 9.7}{0.8 \times 5} = \$36.5$ million/year

24-Hour Equatorial $\qquad \frac{2 \times 10}{0.6 \times 5} = \$6.7$ million/year

The initial costs of individual ground stations are estimated to be $2.5 million for medium-altitude satellites because of the costly tracking antennas required.[25] For the 24-hour stationary orbits, these costs are expected to be less than $1 million [72].[26]

Since the medium-altitude system would cost over $100 million more, and the 24-hour inclined orbit system three times more than the 24-hour stationary orbit system, only the last will be discussed.

Figure 38 shows the total annual operating expense for the 24-hour stationary orbit system as a function of the probability of successful orbit injection. It is assumed that the annual cost of operating the ground station is 20% of the initial cost; since there are expected to be two stations, the annual cost for them is $400,000.[27] In addition, an annual allowance of $100,000 is made for tracking costs.

It seems reasonable to assume that the probability of successful orbit injection will be at least 0.9 by 1980 and probably earlier; thus, the total annual operating costs can be expected to drop 22% in this period.

Figure 38 depicts the annual operating costs averaged over many years. This does not mean that the costs in any given year cannot deviate from the average value. For instance, if a system were to be made operational in 1970, the minimum launch cost for two vehicles could be $20 million, plus $500,000 for ground stations; but considering that there is only a 0.6 probability of successful injection, eight launches would be required to be 99% sure of getting two into orbit. Figure 39 shows how the probability of successful orbit injection affects the

---

[25]NASA information indicates that some similar facilities now in progress will cost between $5 and $10 million.

[26]Some ground stations of this type have been estimated to cost as little as $50,000; this seems unrealistically low.

[27]These estimates do not include the costs of ATC-leased telephone cables or take into account the fact that the ATSAT will be able to carry some traffic otherwise carried by leased lines.
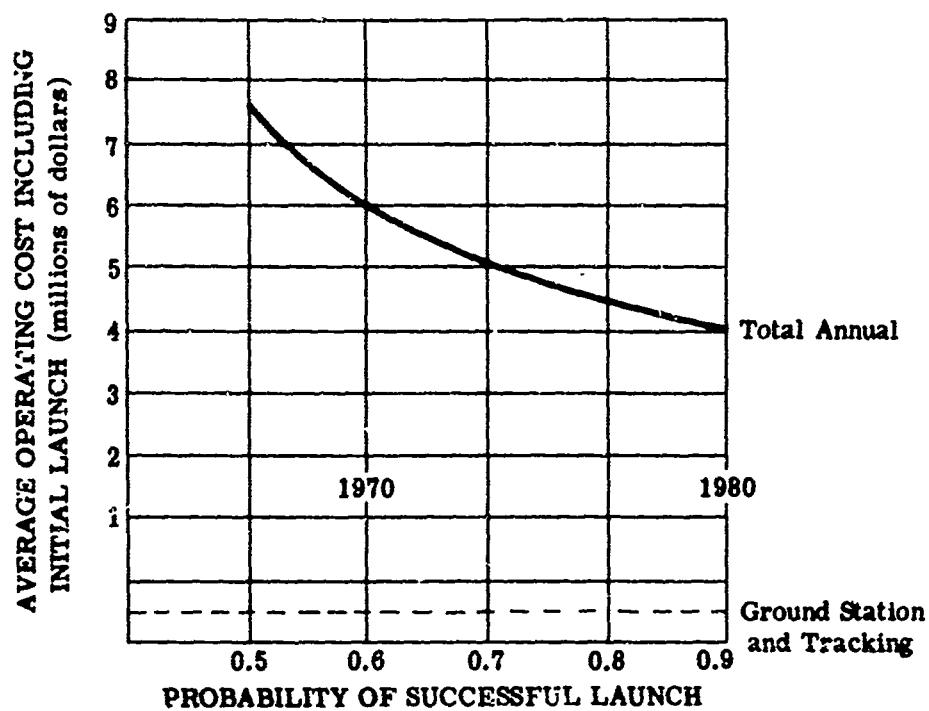
FIGURE 38. ANNUAL OPERATING COST OF STATIONARY SATELLITE
SYSTEM. The years 1970 and 1980 indicate the times by which the indicated
probabilities of successful launch are anticipated.
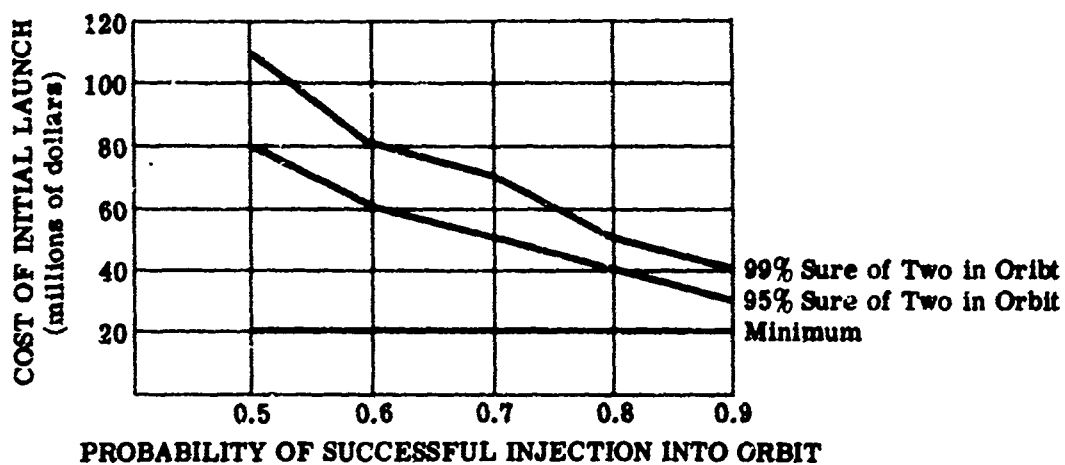
FIGURE 39. PROBABILITY OF ORBITAL INJECTION VS. INITIAL COST

93

initial cost. Note that this does not affect the average costs shown in Figure 38, but merely indicates that the costs for a given year could be very large if there were a series of launch failures.

The costs given so far exclude development costs. The authors believe that $5 million should adequately cover the cost of developing the required aircraft antenna and the satellite communications equipment, but not necessarily the digital aircraft and ground-station equipment.

B.1.5. FUTURE DEVELOPMENTS. One major technical development is anticipated in the near future: three-axis stabilization. This will make possible the use of simpler antenna designs with higher gain and, since flat, oriented arrays are feasible, will reduce solar cell requirements. It is virtually certain that this approach to stabilization will ultimately be used for stationary satellites. The technical problems associated with providing acceptable accuracy and long-term reliability appear so near solution that in planning beyond 1970, three-axis stabilization can be assumed. This study assumes spin stabilization of the satellite because reliable results from this technique can be expected a few years earlier. Also, since spin stabilization poses a more difficult communications problem, it was considered conservative to demonstrate the feasibility of the satellite aircraft relay making use of that technique.

The primary technical limitation on satellite design in the near future is booster payload capability. The present study assumed that the Atlas-Agena vehicle (providing about 370,000 pounds of thrust) would be used. Within a decade, the Saturn C-1 (1.5 million pounds of thrust) and the Titan-3 (3 million pounds of thrust) will provide a capability for much greater orbited weight. Undeniably, the rocket technology represented by these vehicles will be expensive. However, if reusable vehicles are developed, a realistic compromise between cost and payload may be possible

A second major limitation at present is the small amount of electrical prime power available. Only solar or nuclear power appears to be useful for a satellite life of five years, which is a reasonable period in terms of costs and reliability of service. Advanced solar cells may yield a factor-of-four improvement (on a watts/lb basis) over present installations. Nuclear-powered turbo generators of the Snap-8 type may give improvements of the order of 20 to 25. A 60-kw nuclear-powered generator is expected to weigh about 2500 pounds and undoubtedly will be very expensive. Though no price estimates are available, the levels of technology required to produce a reliable nuclear device at weights consistent with space applications will preclude low costs [73].

Since the availability of large amounts of satellite prime power makes UHF links between satellites and aircraft possible, the introduction of the supersonic transport in the late 1960's or early 1970's might be an appropriate time to consider a change in the radio communications for aircraft. This study has assumed that the $500 million investment in present VHF-AM communications systems is sufficient justification in itself to make a strong effort to provide satellite communications that would protect that investment. The actual implementation date for a

UHF system might be 1980, but by the late 1960's the initial planning would permit making provisions in supersonic transport (SST) designs for later installation.

At the risk of appearing unduly optimistic, a post-1975 system will be postulated to indicate what the effect on frequency allocations might be. A nuclear-powered generator of about 100 kw and 4000 pounds is assumed. The satellite might be launched by a large reusable booster directly into a "stationary" orbit, or by a less powerful expendable booster into a low-parking orbit; then it would be propelled by an ion propulsion system (powered by the nuclear generator) into position in a "stationary" orbit, as proposed by RCA. A number of voice and data channels to mobile (aircraft) stations would be provided, as well as point-to-point communications between traffic control centers. Since size of an orbital vehicle is likely to remain a problem for some time, it is assumed that various items would have to be deployed (nuclear generator, electronics, antenna array, etc.). It is possible that the overall balance of costs and performance might necessitate actual assembly in space by men. Present space projects (Gemini, Apollo) lend credibility to such a possibility. Assembly of a three-satellite, world-wide coverage system by a single crew might be desirable in this case. Also, since a project of this magnitude promises to be expensive, limited "manual" maintenance and resupply, perhaps on a module replacement basis, might be technically and economically justifiable.

Nothing in this "future" system indicates a need for revising the frequency recommendations in this report. A VHF capability could be retained as a back-up system since continued use of VHF equipment in the aircraft is assumed. The 1540-1660 Mc UHF band appears to be as good a choice for propagation then as it does now, and there will be sufficient power to overcome the present path-attenuation disadvantages between satellite and aircraft. The ATSAT system recommended makes use of only a limited amount of the available UHF band. As shown above, retaining the entire band may be justifiable on the basis of anticipated use in the future.

B.2. GROUND STATION LOCATIONS

Occasionally, the satellite orbit will coincide with a line between the sun and the ground station. During these periods, communications from the satellite to the ground stations will not be possible, because the ground antennas will "see" a very large sun noise temperature (on the order of 10^{4}°K, as shown in Figure 20, for a 2° beamwidth antenna). These blackouts (which are completely predictable) will last no more than about 10 minutes on any day, and will occur on only 12 days per year (six days in late winter and six in early autumn). Thus, on any given day, the blackout will occur 0.7% of the time, and in a year it will occur about 0.02% of the time. The time of day of the occurrence will be determined by the ground station's location and the satellite's location over the equator. For the coverage indicated in Figure 4, for satellite No. 2, located 30°W, a ground station near New York or Washington D. C. (approximately 75°W) will black out about three hours before noon. A London station, 30°E of the satellite, will black out about two hours after noon.

Note that one of the ground stations will always be able to communicate with an aircraft. The authors do not believe that these brief and highly predictable blackouts impose any serious restrictions on ATSAT operations.

Appendix C
RELAY CONSIDERATIONS

The possible use of intermediate relays to augment the present means for communications in the North Atlantic leads to considerations of basic similarities and differences among the three types of relay systems proposed. Independent of whether ocean vessels, en route aircraft, or satellites are employed, there are two general questions:

(1) Given a configuration of relays, does a communication link exist between an aircraft and the terminal station?

(2) If there is a message to be transmitted between an aircraft and a terminal station, how is the routing determined?

C.1. EXISTENCE OF COMMUNICATION LINKS

In distinguishing among the three types of relays, note that ocean-borne relays are fixed geographically whereas both satellites (except 24-hour stationary orbits) and en route aircraft may vary in position as a function of time. Given an aircraft at any point in the North Atlantic and a configuration of ocean relay, the question of whether the aircraft is within range of a relay is immediately resolved by comparing its location with a map of the coverage of the relay system.

In the case of a nonstationary satellite relay system, the times at which satellites will pass over the area and the amount of coverage provided can be predicted. Hence, although the question whether a satellite relay is in range of an aircraft is a function of both location and time, it is predictable for a given location and a given time. Maintaining and using such predictions becomes more complex as the number of satellites increases. Relaying an aircraft-to-aircraft message depends on a sufficient number of flights en route, distributed in such a way as to provide the necessary communication link. Although knowledge of flight paths can be used at any time to predict the existence of a link between en route aircraft and a ground station, such factors as weather, unscheduled returns to base, and radio equipment failures preclude predictions of communication coverage for any extended period of time.

In emergency situations, airborne and satellite relays exhibit one advantage over a system using line-of-sight transmission to ocean vessels. An aircraft forced by equipment failure to fly at very low altitudes or ditch at sea could communicate with ocean-borne relays only if it were within the reduced line-of-sight range. However, airborne and nonstationary satellite coverage patterns would sweep over the disabled aircraft, providing at least intermittent communication (stationary satellites, of course, provide full coverage at all altitudes).

C.2. ROUTING

When a configuration of relays that provides the desired coverage has been established, the problem of routing messages from relay to terminal stations remains. If it is feasible to

communicate directly between each relay and the terminal stations, only one relay is required in any air-ground-air communication. On the other hand, if the relays can communicate only with adjacent relays, multiple paths to the terminal may exist. In principle, this problem is similar to that of routing long-distance telephone calls in that a number of alternative routings from each relay to the shore station may be established, with preassigned priorities to indicate preferred routes. However, all command and control signaling, as well as messages, must be carried over RF links. Routing messages by a purely random process has been suggested for some relay nets, but does not seem appropriate in this application. Prosser has observed in a number of experiments with a simulation model that long delays are frequently encountered in a communication network using random routing procedures [74]. These experimental results indicate that, if short access times are to be maintained, techniques must be developed for prefacing messages with routing information or relaying messages via pre-assigned routes. In general, the routing problem requires the establishment of standing operating procedures to be employed in deciding which relay will forward a message and in resolving conflicts when faults occur in the network.

Each of the three types of relay systems also has the problem of two or more aircraft attempting to contact a relay at the same time. Two possible ways of resolving this problem are: (1) by providing for a "busy" signal, or (2) by using a roll-call system so that each plane would be contacted on a periodic basis. Evaluating the relative merits of these or other more refined approaches depends largely on the constraints imposed by the assumed system.

Appendix D
MESSAGE CONTENT

The information content of basic position reports is assumed to be:

(a) Message synchronizing
(b) Address
(c) Position information
(d) Flight data

The approximate bit requirements for each of these categories, as well as a tentative estimate of weather reporting requirements, are based on the use of abbreviations wherever possible and a fixed format for routine messages. The information content of a typical position report is presented in Table XI.

The content of weather messages is strongly affected by the existing technology. If weather satellite systems are in full operational use, aircraft data concerning cloud cover may be unnecessary. The type and accuracy of navigational equipment and altimeters have a strong influence on the wind and barometric pressure information which can be usefully reported. The introduction of very-high-altitude supersonic flight may require monitoring and reporting of

97

radiation levels. In recognition of this wide diversity between aircraft types, their need for data, and their ability to obtain it, a "typical" weather message is postulated below and the bit content evaluated.

TABLE XI. TYPICAL POSITION REPORT

Position Report	Number of 7-Bit Symbols Required
(a) Message synchronizing: 21-bit Barker sequence	3
(b) Address: (see Note 1, p. 99)	
Aircraft — 2 letters and 3 numbers	5
Ground terminal — 3 letters	3
(c) Position: (see Note 2, p. 99)	
Present = latitude, longitude	7
Next checkpoint = latitude, longitude, estimated time	11
Landfall or destination = place name, estimated time	7
(d) Flight data: (see Note 3, p. 99)	
Outside temperature = abbreviation, sign and 3 digits	5
Flight level = abbreviation and 3 digits	4
Velocity = abbreviation and 4 digits	5
TOTAL 7-BIT SYMBOLS	50 (i.e., 350 bits)

TABLE XII.   TYPICAL WEATHER MESSAGE

Item	Number of 7-Bit Symbols Required
(a) Temperature — included in position report	--
(b) Barometric pressure — 4 digits	4
(c) Altitude — included in position report	--
(d) Wind:	6
Velocity — 3 digits	
Direction — 3 digits	
(e) Cloud cover:	5
% coverage — 1 digit	
Altitude — 3 digits	
Type of clouds — 1 letter	
(f) Sea state — 1 digit	1
(g) Turbulence encounter:	9
Magnitude = ± and 1 digit	
Location — 7 digits	
(h) Jet-stream encounter:	13
Velocity — 3 digits	
Direction — 3 digits	
Location — 7 digits	
(i) Radiation level — 5 digits	5
(j) One-letter abbreviation to indicate each category above	7
TOTAL 7-BIT SYMBOLS	50

Notes:

1. The use of a 2-letter abbreviation for the airline provides 26^2, or 676, possible airline designations. A 3-digit number following will identify 1000 individual aircraft for each airline.

Similarly, the 3-letter ground terminal call signals are long enough to provide some phonetic clue to the full name. Even if phonetic similarity requires discarding many of the 26^3 = 17,600 combinations, there should be more than enough left to identify the pertinent ATC centers, airports, and ocean-station vessels in the North Atlantic and adjoining regions.

2. The position information is composed of four factors:

    Latitude — expressible in 3 symbols to 1 degree accuracy, i.e., 79°N

    Longitude — expressible in 4 symbols to 1 degree accuracy, i.e., 179°W

    Place name — airport, ATC center, expressed in 3 letters as in address

    Time — expressed in 4 digits to nearest minute, i.e., 2359

3. Flight data are reported by using these conventions:

    A one-letter abbreviation to indicate the item being reported (i.e., flight level = L, velocity = V, temperature = T)

    Four symbols permit reporting temperatures of ±999° (F or C) — an adequate range for in-flight temperatures

    Flight levels are reported in 1000-foot increments with three digits giving a capability for altitudes to one million feet, or for more finely divided levels and a lower maximum altitude

    Velocity is represented in one mph (or knot) increments by 4 digits (maximum = 9999 mph)

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104

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Various means of providing a reliable communication
system for air traffic control (ATC) in the North At-
lantic in the 1970's have been investigated. The study
indicates that considerable improvement in the adequacy
and reliability of communication with over-ocean aircraft
(during the interim period before 1970) could be obtained
by the adoption of an optimized hybrid system utilizing
High Frequencies (in both ground wave and ionospheric
modes); Very High Frequencies (present communication band
in both line-of-sight and tropospheric scatter modes);
and Low Frequencies (ground-to-air). However, the study
also indicates that the only economically and operation-
ally feasible technique which will fully satisfy the
near-future requirements for communication to over-ocean
                                                    (over)

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I.   McClure, George W.
II. Duté, John C.
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Descriptors

Communication Satellites
Air Traffic Control Systems
Radio Propagation

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aircraft and which will be at all adequate for post-1970 requirements, is one which utilizes active satellite relays. The study further indicates that, for the communication function alone, synchronous (or 24-hour period) satellite orbits are superior to other orbits when economics and operational procedures are considered. This system, which provides the necessary area coverage and access time at a reasonable cost, also protects the large capital investment of the airline operators in VHF communications equipment.